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RF INTERFERENCE CONTROL HANDBOOK

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Preface

Although significant advances have been made with RF-interference suppression techniques, the increasing number of electronic devices constantly results in new problems for which established practices are not always applicable. Consequently, RF-interference control has become a significant problem for technicians, engineers, and others involved in electronics systems design, installation, and maintenance.

Recently, a number of newspaper and magazine articles have called attention to some of the more disturbing interference problems. Examples include cases of taxicab dispatchers, radio amateurs, and commercial broadcasters inadvertently causing missile test launchings, premature openings of drone parachutes, and difficulties in satellite tracking.

Since similar suppression techniques are frequently used with so many different types of equipment, descriptions of individual applications are not necessary. Whenever appropriate in this book, discussions of RF-interference control techniques are made without reference to specific equipment; however, sufficient detail is given to permit general application of the techniques. Thus, this book provides enough information on the theory and control of RF interference to permit you to properly analyze different types of interference effects and help you arrive at some intelligent means of minimizing or eliminating them.

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September, 1962

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CHAPTER 1

Theory of RF Interference

Whenever two or more electronic systems employing transmitters and receivers are operated near each other, the possibility of mutual interference arises. This generally results in a loss of information, generation of false information or, in the case of a high-power transmitter, interference with or actual damage to a sensitive receiver.

In addition to interference from equipment which normally is designed to generate some type of RF signal, such as in the case of transmitters (for transmission through wires or the atmosphere), other types of interference are generated by all kinds of electrical equipment, and by the discharge of static charges which develop on insulated surfaces. These are generally of greatest amplitude in the RF spectrum. Such RF interference is electrical disturbances which cause undesirable response or malfunctioning of electronic equipment.

From the standpoint of interference, the two most important characteristics of an electromagnetic disturbance are amplitude and frequency. Most disturbances do not, however, consist of energy at a single frequency. In fact, most troublesome forms of interference are made up of short bursts, or pulses, of energy which involve a large group of frequencies and various amplitudes. The pulse can be resolved into its various components to show that:

1. For a pulse of finite duration, the spread in frequency is inversely proportional to its duration.
2. For any pulse, the more rapidly the amplitude builds up or falls off, the greater is that portion of its energy which is contained in the high-frequency components.
3. For any pulse, the longer its duration, the greater is that portion of its energy which is contained in the low-frequency components.

A graph of the energy present in a disturbance as a function of the frequency is called an "energy distribution curve," or more briefly, "energy spectrum." Such a curve summarizes the pertinent information about a disturbance and is a very useful tool in analyzing interference signals.

Interference from a group of phenomena such as electron-tube noise due to thermal agitation, resistance fluctuations in current-carrying resistors, and atmospheric "static" displays an irregularity in its properties. There are random fluctuations of amplitude about a mean value throughout the range of frequencies. The energy of this type is generally constant at all frequencies, up to a maximum frequency beyond which the energy drops off rapidly to zero.

Most of the interference which will be considered in this book has a degree of periodicity in one manner or another. This does not mean that the source must generate a pure sine wave at any single frequency, however, although this may be true in a few specific cases. It need only be true that there are some characteristic time variables associated with the generation of the interference, such as the build-up time or duration of a pulse, or the time lapse due to successive commutator segments passing a brush.

INTERFERENCE GENERATION

Interference signals are caused by varying electric and magnetic fields. A varying electromagnetic field is the result of non-uniform motion of electric charges—that is, a varying electric current. To determine the origin of the interference, it is necessary to determine the causes of the variations in electric current.

An electric current may flow either in a conductor (conduction current), in a gaseous dielectric through which charged particles are moving (convection current), or in a dielectric that has no free charges (displacement current). Displacement currents are negligible at most frequencies and need be considered only in connection with radiation and other phenomena associated with very high frequencies. The currents which are most important as sources of RF interference are convection currents (which occur in electron tubes, arcs, and sparks) and conduction currents.

The latter two forms of electrical current may be computed by application of the basic Ohm's-law equation, $I = E/Z$, in which the current, I, is considered to be the effect produced by the electromotive force, E, against the opposition of the impedance, Z. This equation shows that there are two basic processes from which interference may originate. One is the generation of varying electromotive forces, and the other is the varying of impedance.

Varying Emf

The three important generators of varying emf are rotating machinery, vacuum-tube oscillators, and nonlinear impedances.

In all rotating machinery, there is relative motion between a set of conductors and an associated magnetic field. An emf is induced in the conductors, which may be computed according to the basic law:

$$E = BLv$$

where,

E is the induced emf,
B is the magnetic flux density,
L is the effective length of the conductor perpendicular to the field,
v is the component of relative velocity perpendicular to B and L.

Ideally, in an AC machine the variation is such that the generated voltage is a pure sine wave. In a DC machine the variation is such that the generated voltage at the output terminals is constant while the brushes slide on any one commutator segment or from one segment to the next.

Actually, deviations from the ideal are always present in both machines. The peripheral velocity of the conductors is not exactly constant, the effective length of the conductors is not always exactly the same for all conductors, and the magnetic flux density does not vary exactly sinusoidally. Thus, irregular variations occur in all three quantities making up the right side of the foregoing equation, $E = BLv$; as a result, the generated emf always contains undesirable variations. These are kept to a minimum by optimum design of the machine.

An additional difficulty arises in DC machines. Even if the ideal is approached very closely and the output voltage appearing at the brushes is free from any ripples, the voltage induced in the conductors must jump abruptly from one constant value to another each time the brushes jump from one commutator segment to the next. As a result, the current in the armature will fluctuate very rapidly and therefore be quite rich in harmonics, even though the external current may not. This is one of the reasons why DC machines are more troublesome in generating RF interference than are AC machines.

Vacuum-Tube Oscillators

The frequencies required for the normal operation of many types of electronic equipment can often cause interference in the form of unwanted signals in other equipment, even though the oscillator is an ideal one that generates a perfect sine wave. If the oscillator is not ideal, additional interference will be generated. Thus, oscillators are likely to be the source of interference by virtue of the very function they are designed to perform.

Nonlinear Impedances

Impedances dependent on currents through them or voltages across them are called *nonlinear impedances.* These impedances act like generators because they always produce harmonics.

The situation becomes more complicated when the impedance is a function not only of the current but also of the rate at which the current changes in nonlinear inductances. The net results are the same, however. Therefore, any nonlinear impedance must be considered a possible source of interference.

Variation of Impedance

Even linear impedances which are independent of the current through them may vary in magnitude due to some external process. Although these impedance changes are usually resistive, changes in reactive impedances may also be troublesome. There are two important instances of interference-generating impedance variations:

Brushes—Electrical contact between circuit components that are in relative motion to each other is made by brushes that ride on slip rings or commutators. The impedance of this junction depends both on the pressure applied and on the area of contact. Uneven wearing of the contact surfaces (even on a microscopic scale) and pressure fluctuations due to mechanical vibration cause undesirable variations in impedance. As a result, any brush and slip-ring or commutator combination constitutes a serious source of RF interference.

Electronic Devices—A vacuum tube or gas-filled tube is used in many applications to produce a switching action. Such tubes are particularly useful as generators of nonsinusoidal waveforms, finding application as pulse generators, modulators, and oscillators. Here the generation of harmonics is desired and is, in fact, essential to proper operation of the device. It is not surprising, therefore, that these devices also rank high as generators of RF interference.

An undesired variation of impedance may also occur in vacuum tubes used as sinusoidal generators. Because of the nonlinearity of the tube characteristics, there are always harmonics generated in an electronic oscillator, together with the desired frequency. The larger the power output of the circuit, the more difficult it becomes to reduce the harmonic content. Consequently, the last stage of a transmitter or similar device is most likely to produce interference.

Mechanical Switches and Commutators

When a switch is operated the impedance in the circuit changes suddenly from practically zero to infinity, or vice versa. The currents and voltages in the circuit must then readjust; but if reactive elements are present, this shift cannot take place instantaneously. A short interval occurs during which the voltage and current change very rapidly. Such temporary variations, called "transients," are closely related to pulses which are rich in harmonics and that act as interfering frequencies.

One of the most important examples of an interference-producing switching process is commutation in rotating machinery. The function of a commutator is to switch the electrical output terminals on the armature from one segment to another in such a way as to keep the current and generated voltages as constant as possible. During such processes, even under ideal conditions, DC machines with commutators must be a source of interference in three distinct ways:

1. The current in the armature undergoing commutation must change rapidly, since it completely reverses direction.
2. The voltage generated must vary, since the voltage induced in each coil varies with the position in the magnetic field.
3. The total armature impedance between brushes must change, as some of its coils are short-circuited by the brushes.

In addition, there are many opportunities for interference to be generated due to deviation from the ideal. For example, the voltage induced in the coil undergoing commutation may not be exactly zero, or there may be arcing at the brushes.

Arcs and Discharges

When the electric-field intensity in a dielectric between two conductors exceeds the breakdown strength, an arc occurs. The result is very rapid and large variations in the impedance of the path between conductors. Relative to RF interference, this process is most important for gaseous dielectrics because arcing occurring in solids or liquids usually means failure of the system.

The speed of impedance variation during arcing depends on both the external circuit and the ionization or deionization time of the gas. Individual arcing occurs, for example, if the voltage between two conductors of a switch is high enough to ionize the surrounding gas, and if the switching time is greater than the ionization time. This type of arcing may occur in all the switching actions previously discussed and even in the case of brushes, if the vibration is sufficient to break the electrical contact. It may also occur in belt-driven machinery when static charges, built up on the belt, discharge by arcing.

Where conductors at high potential are used in a gaseous atmosphere, there is danger of corona discharge. This type of discharge does not require the presence of another conductor for its occurrence. The potential gradient near the conductor causes the gas ions to move either forward or away. If the accelerated ions are able to ionize a sufficient number of molecules during this motion, the gas will become conductive and allow curent to flow from the conductor into the atmosphere. This phenomenon takes place at potential gradients less than those required for arc discharges; such gradients depend on the pressure, humidity, and temperature of the surrounding gas.

INTERFERENCE TRANSMISSION

A study of interference transmission concerns the manner in which an interfering signal may be carried from a source to a receiver.

Circuit Coupling

Two circuits are said to be coupled when currents or voltages in one produce corresponding voltages or currents in the other. Accordingly, two circuits may be coupled either by a mutual impedance or a mutual admittance.

A mutual impedance exists when the current flowing in one circuit produces a voltage in the second circuit. Its magnitude is the ratio of the open-circuit voltage of the second circuit (with all other voltage sources removed) to the current in the first circuit.

A mutual admittance exists when the voltage between one point in one circuit and some reference point produces a current to or from a point in a second circuit. Its magnitude is the ratio of the resulting current at the second point to the voltage at the first point.

Mutual Impedance—Resistances, capacitances, inductances, or any series or parallel combination of these elements may serve as a mutual impedance. In practice, the only elements of importance in RF interference are mutual inductances and the mutual impedance of a common ground (which may arise, for example, from inadequate bonding).

Analysis of the mutual inductance between two circuits shows that while it varies initially in some complicated manner with the distance between the circuits, when the distance becomes large the mutual inductance falls off inversely as the square of the distance.

Mutual Admittance—The most frequently encountered types of coupling which permit interference transmission by mutual admittance are those due to capacitance and induction. Although the definition of mutual admittance implies that the two circuits must have a common ground connection, the elimination of all ground connections from one circuit will not prevent the effects of mutual admittance. This is because without perfect shielding, capacitance exists to some metallic object and will provide a return path for the RF current through the mutual element. The capacitance between the two circuits falls off somewhat more slowly with distance than that indicated by the inverse-square law.

Whenever there is a direct connection between two circuits and a return path exists, conduction current may flow between the circuits. (The return path may be another metallic lead, a mutual capacitance, or a common ground return.) The magnitude of the resulting current depends on the potential difference between the points of exit and entry in the exciting circuit, and on the total loop impedance between these two points.

A common example is the transmission of interfering signals between power and control leads, both out of the interference-producing generator and into the receivers. The circuit in Fig. 1-1 illustrates how an interference signal may be transmitted from a motor to a receiver when both are connected to the same power source.

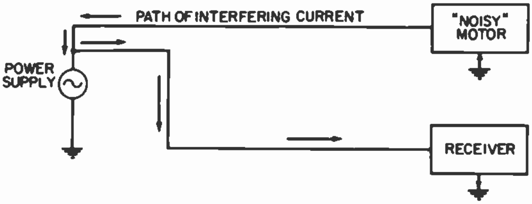


Fig. 1-1. Transmission of an interfering current by direct conduction.

Radiation

The term *radiation* describes the phenomenon of electromagnetic energy spreading out from a source according to the laws of wave propagation. The term *radiated noise* is so commonly used to mean "any interfering signal detected through the medium of an electric or magnetic field" that it is difficult to actually separate the terms *radiation* and *radiated.*

In order to clarify just what constitutes radiation, it is necessary to introduce three fundamental quantities of length as shown in Fig. 1-2. These are:

a, the radius of the smallest sphere that can enclose all of the source,

r, the distance to the point of observation from the center of the source,

λ, the wavelength of the radiation, given numerically as the quotient of the velocity of light (3×10^8 meters per second) divided by the frequency of radiation.

If the field is considered at a point source where r is much larger than a, there will be three contributions to the electromagnetic field:

1. The static dipole field, which varies as $1/r^3$.
2. The induction field, which varies as $1/r^2$.
3. The radiation field, which varies as $1/r$.

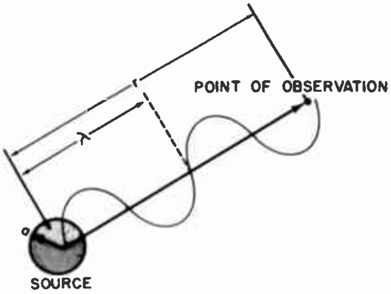


Fig. 1-2. Quantities of length in radiation problems.

The relative importance of the three terms depends on the ratio of r to λ. When r/λ is much larger than unity, the static and induction terms are negligible. When $r/\lambda = 1/2\pi$, the induction and radiation fields are equal.

The radiation field, as its name implies, represents that energy which actually escapes from the source. If radiation takes place in all directions, its intensity falls off inversely with the square of r. The energy in the static and induction fields, on the other hand, remains in the vicinity of the source and provides a strong "sphere of interference" around it of a radius $\lambda/2\pi$.

INTERFERENCE RECEPTION

In considering the final effects of interference—the actual nuisance value—the most important factors are its magnitude relative to that of the desired signal, and its frequency. Most systems are sufficiently linear that the nuisance value of the interference at the output terminals is directly proportional to the input magnitude (above a minimum threshold value).

The band of frequencies throughout which a receiver is sensitive to interference is much wider than what is normally considered its bandwidth. The attenuation of frequencies outside the normal acceptance band is never infinite; there is insufficient rejection of large interfering signals, even though their frequencies may be considerably removed from those the receiver is designed to accept.

Another way an interfering signal may gain entrance is by undergoing a frequency translation during transmission. It may combine with some other signal in a nonlinear element to produce entirely new frequencies which fall within the acceptance band of the receiver. Thus, it becomes necessary to regard signals of all frequencies as having a potential nuisance value.

The input stage of a receiver is designed so that signals within its normal bandwidth will be passed with a minimum amount of distortion; the attenuation is fairly uniform for all frequencies within this band. Since the frequency spread of a pulse varies inversely with the pulse duration, very short pulses contain many frequencies. Those pulse frequencies which do not lie within the acceptance band will be attenuated much more than those which do. As the pulse passes through the receiver, its frequency spread becomes much smaller due to this attenuation. Therefore, its duration becomes longer and the narrower the acceptance band of a receiver, the longer the pulse time at the output. This phenomenon actually occurs in receivers and is called "pulse lengthening."

CHARACTERISTICS OF INTERFERENCE RADIATORS

RF interference sources can be of any impedance; however, to maintain reasonable simplicity, consideration will be given here only to the three major types.

High-Impedance Radiators

The class of high-impedance radiators includes all conductors that contain a large series impedance on which high RF voltages may be developed, with respect to ground, with comparatively little flow of current. Typical items in this category include interconnecting leads that terminate in high impedances, ungrounded control shafts, and poorly grounded equipment cases.

The field which surrounds this type of source is considered to have a high value of wave impedance and is characterized by a large electric component and a small magnetic component. Wave impedance is the ratio of the electric to magnetic components which are transverse to the direction of propagation. For RF interference considerations, however, it is sufficient to consider the relative amplitudes of the electric and magnetic fields regardless of direction of propagation, since interference sources are complex and in many cases a number of radiators are involved.

Whether a given electromagnetic field is considered high or low impedance is determined by comparison with the intrinsic impedance of the medium surrounding the field (for free space or air, 376.7 ohms). The characteristic of the high-impedance field which is of greatest interest in RF interference control is the inclusion of very little current in low-impedance circuits. Shielding is very effective for this type of field, and shielding efficiencies of 100 db are easily obtained with comparatively poor shields.

Low-Impedance Radiators

Low-impedance radiators are any metallic conductors which make up a closed loop and permit large RF currents to flow with little voltage developed. Low-impedance radiators are characterized by large magnetic components and small electric components. The characteristics of this field of greatest interest are its capability for inducing large currents on, or in, low-impedance surfaces or circuits, and its inability to induce large voltages in high-impedance circuits.

Typical low-impedance radiators consist of such items as cable shielding, low-impedance circuit leads, and metallic equipment cases. Adequate shielding of this type of field is the most difficult to obtain and varies from 36 to 50 db for a single layer copper braid used at frequencies of 150 kc to 1000 mc.

Complex Radiators

The complex radiator (both high and low impedance) as a type of RF interference source, is considered here because of the complexities encountered when interpreting its effects on certain pickup devices. Any length of lead on which standing waves are produced represents a complex radiator. At low frequencies, complex radiators are usually found in radar and other systems having numerous interconnected components. Shielding this type of source is difficult for low impedances but simple for high-impedance radiators.

CHARACTERISTICS OF SENSITIVE EQUIPMENT

Radio, television, and radar receivers are almost invariably caused to malfunction by RF interference. This is due to the very low-level circuitry contained in these devices. Paths through which signals are coupled into the receivers include the antenna, its lead-in, the receiver case, and power or control leads. Interference and susceptibility tests provide satisfactory controls over interference signals on the power leads. For this reason, only the other paths of entry will be considered here.

The principal receiver component affected by high-impedance fields is the unshielded antenna lead-in. Even the usual poorly designed receiver case or single-layer copper braid found on coaxial antenna cables provides more than adequate shielding against high-impedance fields. The only other way a receiver can be affected by high-impedance fields is by direct radiation through an opening in the space between the source and antenna.

In any event, the interference problem caused by the high-impedance field is the easiest to solve.

If a grounded lead is run adjacent to either the antenna or its lead-in, reduction of the interfering signal by 30 db is easily achieved. Similarly, proper application of a capacitor to a high-impedance generator will provide very satisfactory suppression. Other simple but highly effective procedures include dressing leads close to the ground plane, and isolating them by utilizing metal barriers or by keeping them far apart. If interference from a low-impedance field affects an unshielded lead-in, the problem is no longer simple and may require shielding the lead-in or shielding and filtering at the interference radiator.

At frequencies above 30 mc, interference which enters a receiver usually penetrates the shield of the coaxial antenna cable. The design of modern communication systems requires many long lengths of connecting antenna cable. Large numbers of leads and cables are usually routed together without regard to interference emission or interference sensitivity. Interference currents present on low-impedance conductors that are routed adjacent to antenna cables have maximum capability for penetrating the cable shields and causing receiver malfunctioning.

Tests show that broad-band interference, coupled in this manner from 500-ma inductively loaded relay contacts, can cause undesired signals in a receiver (of typical bandwidth) exceeding 200 microvolts peak over a considerable portion of its frequency range. Effective shielding against interference voltages existing on adjacent high-impedance leads is provided by the cable shielding.

Entry of interference into receiver circuits through the case is a coupling problem quite similar to penetration of the antenna cable shield. This trouble is much less likely, however, since the receiver is comparatively small and interfering currents must flow close to the case in order for signals to penetrate it. Shielding efficiency of the average communications receiver is approximately 40 db for low-impedance fields and in excess of 100 db for high-impedance fields.

CHAPTER 2

Interference Measurements

Two of the first steps in suppressing RF interference are to determine its type and origin. The sounds produced by the output of a sensitive radio receiver permit the interference to be classified, providing a definite clue to its source. Man-made disturbances produce certain classes of sounds, each characteristic of a specific type of electrical equipment. The information provided in this chapter may be used as a guide for locating the equipment that is creating the interference. Thus, when a "popping" noise is being received, an ignition system would be investigated rather than a generator.

After identifying the type of interference being received, it is necessary in some instances to locate the exact source before suppression measures can be applied. For example, if an ignition system is identified as the interference source, the leakage may result from inadequate shielding or incomplete grounding of the coil housing. If a generator is identified as the source, the exciter brushes or slip-ring brushes may require suppression. Consequently, the offending source must be pinpointed before appropriate suppression technique can be applied. The interference source can be located by means of a receiver with a probe antenna and by isolation.

A probe antenna restricts pickup of the receiver to interference produced in a particular vicinity. Thus, by moving the probe to different parts of an ignition system or a radio transmitter shield, it is possible to locate the leakage.

ISOLATION AND IDENTIFICATION

Isolation consists of deactivating each possible source, one at a time, and identifying the offending member when the interference ceases. For example, in an engine-generator it is possible to decouple the engine from the generator, lift the generator or exciter brushes, disconnect the voltage regulator, or take other similar steps to isolate each source of possible RF interference.

Table 2-1 lists various types of noises heard in a receiver, together with the possible sources.

Ignition Interference

A fast, steady "popping" sound in the receiver output is characteristic of the noise produced by an ignition system. This sound is in step with the engine speed and is easily recognized. Ignition noise ceases the instant the ignition switch is turned off.

Table 2-1. Types of noise and possible sources.

Noise	Source
Regular or irregular clicking	Electric calculating machines Mercury arc rectifiers Relays Switches Teletype machines Thermostatic controls Electric typewriters
Popping	Ignition systems Magnetos
Buzzing	Bells Buzzers Vibrators
Crackling	Regulators
Whining	Devices using motor-generators
Loud continuous sputtering	Arc welders High-frequency apparatus (diathermy, etc.) Arc lamps

Alternator and Synchronous Motors

Brush sparking at the collector rings of an alternator or synchronous motor produces a type of RF interference which can best be described as RF "hash." This is sometimes confused with atmospheric disturbances, but can be recognized by listening carefully. The alternator exciter is characterized by a steady "hash," or whine. Commutation-ripple interference is not so distinct as ignition interference; however, you will seldom confuse the two. Brush sparking and commutator ripple of a DC generator produce RF interference similar to exciter noise.

DC Generators and Motors

Fast-running DC generators and motors have a high-pitched whine corresponding in pitch to the running speed. The noise is similar to exciter interference in an alternator. Slow-running generators are characterized by a loud, continuous sputtering. By varying the speed, a listener can detect the origin of this interference.

Voltage and Current Regulators

Regulators which employ vibrating contacts produce a distinct, intermittent "popping" sound in the receiver headset. This sound is more pronounced than that from the ignition system and does not vary as critically with engine speed.

Relays, Switches, and Thermostatic Controls

Devices such as relays, switches, and thermostatic controls that normally make and break contact between two metallic parts produce a *clicking* sound in a receiver. This clicking is characteristic of all switching devices and may be regular or irregular, depending on whether the switching is occurring at a constant, cyclical, or intermittent rate.

TESTING AND SAMPLING

The purpose of RF-interference testing is twofold:

(1) To determine the amount of interference generated by the equipment or component under test, and transmitted from it by radiation or conduction, so that suppression techniques may be applied in a manner best suited to each case.
(2) To determine whether the equipment complies with permissible limits of radiated and conducted interference.

Radiated-interference measurements must be carried out at a location which is as free as practicable from outside sources of interference. The use of shielded rooms was at one time considered the best means for providing an interference-free location; because of the disadvantage caused by reflections, resonances, and other disturbances however, this method has given way to the use of outside areas, carefully selected for their isolation from buildings, as well as power and communication lines.

A vast amount of experience gained in the study of RF interference problems has led to the establishment of standard testing procedures and equipment. The very nature of RF interference precludes any possibility of using a single quantity to describe all its properties. However, those properties which affect communications have been determined, and means of stating and measuring the associated parameters in terms of a single unit of measure have been evolved. The extent to which suppression must be accomplished for satisfactory operation has also been determined after considerable study and many field tests.

The limits imposed on equipment must provide for adequate protection of communications, with a reasonable safety factor to allow for minor variations in production and deterioration in service. Since interference-suppression requirements often have contractual implications, these limits must not be in the nature of a goal for a manufacturer to shoot at, but rather must be practical values, consistent with mass production and economy. In addition, the units of measure, measuring techniques, and instrumentation must be such that the test results are not subject to continual change.

A manufacturer is concerned with producing his equipment to conform with RF-interference suppression requirements. The first procedure he should follow consists of determining the minimum requirements for interference suppression and the applicable techniques. Next, he should apply, to a pilot model of his equipment, those techniques which adequately suppress all probable sources of interference. The application of one, or even more than one, suppression technique does not always guarantee that the equipment will meet the minimum requirements.

BASIC MEASURING TECHNIQUES

Most of the serious interference produced by electrical equipment of today is the impulse type. The peak value of impulse interference is the quantity that has to be measured to evaluate the interference-producing capabilities of industrial and civil electronic systems. This is contrary to standard practices before World War II, when the major concern was merely the nuisance value of interference to radio and television, for which purpose a detector-metering circuit called "quasi peak" was employed. This quasi-peak device produces a meter indication which increases with the repetition rate of the interference pulses and which is, according to listening tests on broadcast interference, a measure of the nuisance value of the interference. With an instrument of this type, however, impulse interference having a high peak amplitude at a low-repetition rate produces only a slight meter indication, although it is capable of considerable interference with communications.

Since most broad-band interference sources produce impulse-type interference, and since the response of a receiver (and noise meters as well) to impulses is proportional to bandwidth, it is necessary to measure and specify the peak value of the interference on a spectral sampling basis, in volts per unit bandwidth. In order to measure interference in these terms a new concept, employing instruments of the type to be described later, must be used.

Antennas

Placement of antennas for measuring radiated interference is determined empirically, the antennas being placed close to the equipment under test, with the limits adjusted accordingly to afford a better ratio of limit interference to ambient interference.

The antennas used in measuring radiated interference should be comparable to those most widely used by portable communications equipment. A broad-band antenna speeds up testing time appreciably and also affords scanning over a wide frequency range, which is not practical with tuned antennas such as resonant dipoles. The term "per meter" is not used in prescribing the units or limits, inasmuch as the interference is measured close to the source with the measuring equipment antenna in a nonuniform field over its physical length. The theoretical "effective height" of an antenna under such conditions is meaningless; hence, applying a height correction factor to measurements so obtained would be fallacious. The units of measure for broad-band interference are therefore simply expressed as so many microvolts per kc- or mc- bandwidth with a prescribed antenna placed in a specified manner.

Conducted Interference

Conducted interference is measured at the power terminals, where it might be directly or indirectly conducted into receivers through the power cables. Measurements are made with a two-terminal RF microvoltmeter having appropriate coupling and impedance-matching networks. Conducted-interference measurements are limited to 40 mc. At higher frequencies lead effects, and other stray parameters greatly affect the accuracy of measurement. Since, in practice, the length of leads cannot be prescribed for all equipment, erroneous results might be encountered in many cases. Furthermore, the problem of conducted interference is less serious above this range, where filtering of receivers is readily accomplished with small components.

EXCERPTS FROM INSTITUTE OF RADIO ENGINEERS STANDARD

51 IRE 17.S1

This standard prescribes a system of measurement for spurious radiation, which allows for a high degree of reproducibility of results. The method described is best suited for those devices which will produce an appreciable electric field (in the UHF-VHF bands) at 100 feet.

Setup Details

Transmitting Set-up—The unit under test is placed on a platform 48 inches above the ground and situated on a level surface. A dipole antenna made of ½-inch OD copper tubing, 58 inches from end to end and placed at the end of a 30-foot portable mast (made of non-conducting material), is used as the transmitting antenna. A transmission line of the same characteristic impedance as the one normally used with the unit under test is attached to the center of the dipole and brought down the side of the mast to the antenna terminals of the unit, as described below.

The transmitting line is brought down to a point 84 inches off the ground and bent horizontally for a distance to maintain it at least six inches from the test unit, then bent vertically again and brought down until it is opposite the antenna terminals. At this point it is bent horizontally and attached to the terminals. The total length of the transmission line is 28 feet.

Receiving Set-up—A field-strength meter with a dipole antenna adjustable for horizontal or vertical polarization is used. The antenna is set up so that it can be varied in height from 7 to 20 feet above the ground. The transmission line from the antenna is run horizontally 24 inches away from the test unit and then vertically down to the meter. The receiving-antenna set-up is placed 100 feet away from the transmitting antenna.

Power Supply and Miscellaneous Details—Power lines to both the test unit and field-strength meter are buried at least 12 inches below the ground, with the outlets not more than 18 inches above. The outlet at the test unit is placed no farther than 12 inches from the transmitting antenna. The power lines should be adequately filtered to prevent radiation to the field-strength meter. The line voltage is maintained within 2% of the rated voltage.

In fabricating each of the antennas, metal objects (such as nails) longer than six inches cannot be used.

Measurements

The measurements are to be made under the following conditions:

1. The transmission line connected directly to the antenna terminals of the test unit.
2. The transmission line reversed at the antenna input terminal.

3. The antenna terminals terminated by a noninductive resistor equal to the input impedance of the unit under test.
4. The unit is to be checked over its frequency range at a sufficient number of frequencies to insure determining the maximum radiation within its range.

The field-strength meter is tuned to the frequency of the spurious radiation being measured, and with its antenna aligned broadside to the receiver under test and 20 feet above ground, the test unit and its dipole antenna are rotated together in a horizontal plane until maximum signal is obtained at the field-strength meter. The antenna of the field-strength meter is then lowered from 20 feet to 7 feet while being held broadside to the test-unit receiver. The maximum reading of field strength is recorded as the radiation strength of the receiver under test.

The above tests are to be repeated with the field-strength antenna aligned for vertical polarization.

EXCERPTS FROM INSTITUTE OF RADIO ENGINEERS STANDARD 54 IRE 17.S1 AND AMENDMENT 56 IRE 27.S1

This standard and its amendment establish a method of testing for conducted interference emanating from the test unit over its AM broadcast range (540 to 1650 kc).

Set-Up Detail and Measurement Procedures

The equipment under test is located inside a screen room which has adequate shielding and power-line filtering, with minimum inside dimensions of 7 feet high by 7 feet wide by 10 feet long.

To make the necessary conducted measurements, a field-strength meter capable of measuring voltage with respect to ground is used. The meter must have a nominal bandwidth of 10 kc or less and be capable of internal or external calibration.

To ensure reproduction of the test results, a standard power-line impedance network is inserted in the AC input lines between the test unit and field-intensity meter. The network is the one specified by Amendment 56 IRE 27.31 (see Fig. 2-1). The leads from the test unit

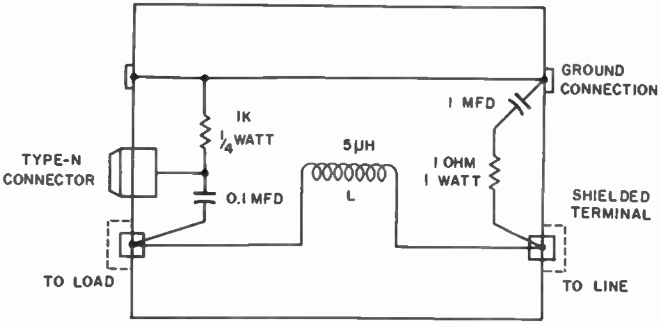


Fig. 2-1. Line-impedance network.

to the impedance network are made as short as possible, and any excess lead length is wrapped around binding posts on top of the impedance network.

Measurements are made (using the field-strength meter) at each of the impedance networks (points *A* and *B* in Fig. 2-2) over the frequency range of interest at a sufficient number of frequencies to insure compliance of the test unit.

MEASUREMENT OF TRANSMITTER AND RECEIVER SPURIOUS EMISSION

The experimental techniques involved in measurement of spurious emissions from AM and FM receivers and transmitters so that they will meet the requirements of the FCC *Rules and Regulations*, are of considerable interest and value.

With the constant increase in size of the radio spectrum, due to the more numerous RF devices, the FCC has found it necessary to regulate the permissible magnitudes of RF interference which may emanate from these devices. This is necessary to insure compatible operation of various components in a complex communications system, and of any sensitive receiver within its range. These rules and regulations require that devices capable of generating RF energy be *certified* in compliance with the FCC's requirements.

Part 15 of the *Rules and Regulations* specifies the conditions and the methods for testing any incidental or restricted radiation device that falls outside Section 301 of the Communications Act of 1934 and therefore may be operated without a station license.

Two definitions are given in Part 15 which are of interest here. The first, for an "incidental radiation device," is any de-

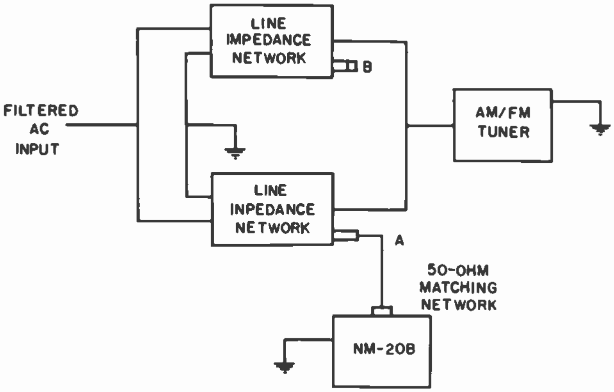


Fig. 2-2. Conducted test setup.

vice which radiates RF energy in the course of its operation, although not intentionally designed to generate RF energy. The second is for a "restricted radiation device," one in which the generation of RF energy is intentionally incorporated into the design and in which the energy can be conducted along wires or radiated.

Because of the nature and variety of devices which can be defined as incidental radiators, the only requirement designated in Part 15 is that they shall be operated so that the radiated RF energy does not cause harmful interference. In event harmful radiation is caused, the operator of the device shall promptly take steps to eliminate it.

Harmful radiation is defined as "any radiation or induction which endangers the functioning of a radionavigation service or safety service, or obstructs or repeatedly interrupts a radio service operating in accordance with the rules set forth in Part 2 of the FCC *Rules and Regulations*."

In the case of restricted radiation devices, Parts 15 and 18 set forth definite radiation-interference limits which must be complied with. In event of harmful radiation from a certified radiation device, the operator must take corrective steps or he may be required to cease its operation.

The particular requirements which an AM or FM receiver must meet are set forth in Subpart C of Part 15, entitled "Radio Receivers" and dated April, 1959.

Interference Limits

In the range from 70 to 130 mc, which includes the FM broadcast frequencies, the test unit shall not exceed a radiated field strength of 50 microvolts per meter at a distance of 100 feet or more. In the range of 450 kc to 9 mc, which includes the AM broadcast band, the RF voltage measured between each power line and ground at the power terminals of the receiver shall not exceed 100 microvolts, pending development of suitable measuring techniques for measuring the actual radiation in the band from 450 kc to 25 mc.

In addition to the measurements described above, and in the case of measurements in the field, the spurious radiation in the AM broadcast band shall not exceed 15 microvolts per meter, measured 15 feet from the power line feeding the unit.

Measurement Procedures

A group of tests can be performed to evaluate the interference susceptibility and elimination characteristics of AM and FM receivers and transmitters. These tests can be used:

1. To verify the desirable characteristics of the equipment.
2. To evaluate the interference characteristics of the equipment.
3. To select from these data usable frequencies or to predict interference.

AM Receiver—These tests performed on a typical AM receiver are:

A. Desirable characteristics.
    1. Sensitivity.
    2. Weak-signal selectivity.
    3. Electric fidelity.
    4. AVC characteristics.

B. Interference susceptibility tests.
    1. True selectivity.
    2. Intermodulation.
    3. Impulse response.
    4. Susceptibility.

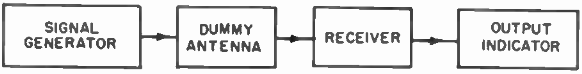
C. Interference elimination.
    1. Spurious emissions.
    2. Conducted signals.
    3. Case radiation.

The tests listed under *A* are, in most respects, standard IRE tests; however, there are some important differences that should be noted. In each case, the quantity measured at the output of the receiver is a 6-db (signal-plus-noise/noise) ratio at the rated output power of the set. Thus, any distortion introduced by the set tends to degrade performance when tested in this manner. It is important that the set volume control be adjusted so the rated output power of the receiver is obtained, if possible. Of the remaining interference susceptibility tests, only the selectivity test will be described in detail here.

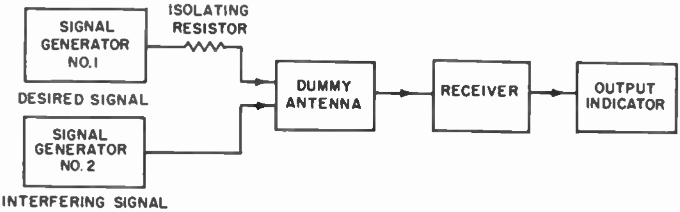
It should be observed that all the tests are performed with a desired signal in the passband of the receiver. Moreover, the quantity measured is not the amount of interference, but the amount of desired signal necessary to overcome this interference. The method for making measurements with a desired signal in the passband is adapted because this is the manner in which a receiver is generally employed. For example, there is a considerable difference between the results of the test for interference conducted with and without the desired signal in the passband. A little thought will reveal that the largest voltage present in a receiver is at the intermediate frequency; therefore, this is the voltage most likely to be found on the power leads. Fig. 2-3 shows a block diagram of the test set-ups for all AM and FM receivers using the procedures described here.

The two-signal test set-up is used to perform the true selectivity test from which most of the interference prediction data are obtained. This test is performed in the following manner:

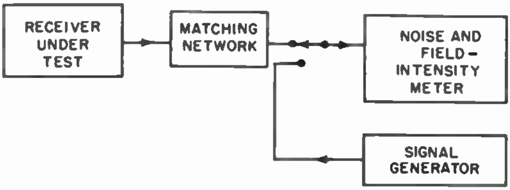
The output of signal generator No. 1 is adjusted until a 6-db (S + N)/N ratio is obtained at the output of the receiver. No. 2, the interfering signal generator, is then adjusted to a predetermined level, such as 1 volt. Its frequency is then varied from 150 kc to 1000 mc. Each time desensitization, cross modulation, spurious responses, or insufficient selectivity re-



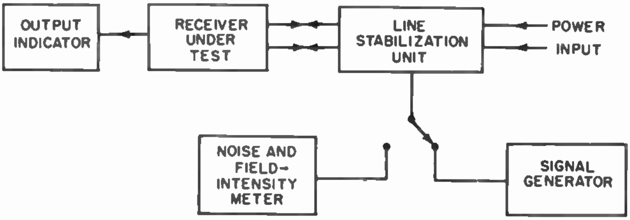
SINGLE SIGNAL-GENERATOR TEST SETUP



TWO SIGNAL-GENERATOR TEST SETUP



SPURIOUS-EMISSION TEST SETUP



POWER-LEAD-INTERFERENCE TEST SETUP

Fig. 2-3. Block diagram for receiver tests.

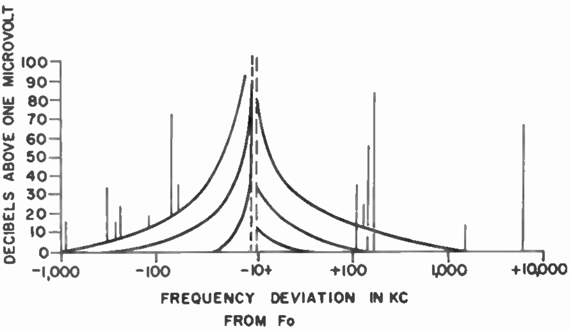


Fig. 2-4. Receiver true-selectivity curve.

duces the output ratio, the output of signal generator No. 1 is increased until the original 6 db (S + N)/N is restored. It is the output level of this signal generator that is recorded. A typical true selectivity curve is shown in Fig. 2-4.

The vertical lines separated by more than 1 or 2 mc from the tuned frequency represent spurious responses. The curves near the tuned frequency represent the combined effects of desensitization, cross modulation, and breakthrough. A better way of describing this portion of the curve is to say that it reveals the true selectivity of the receiver in the presence of interference. Fig. 2-5 is an example of how this information can be used to predict the effects of introducing a transmitter into the receiver environment.

As indicated in Fig. 2-5, if it is desired to operate a transmitter at a frequency of f_{TX}, the power output of which in dbm is *A* and the antenna of which is separated from the receiver antenna by *B* db, then the desensitization is *C* db. Or, stated differently, the introduction of a transmitter at a frequency f_{TX} which induces an open-circuit voltage of 1 volt into the receiver antenna will require an increase of *C* db in the de-

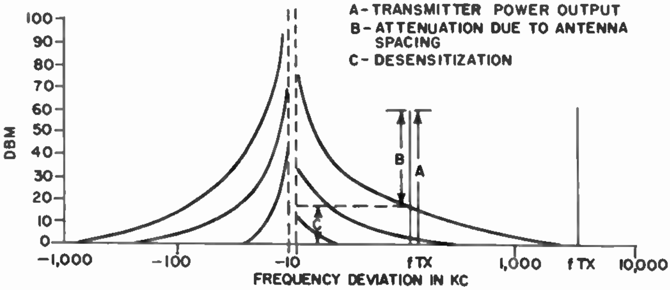


Fig. 2-5. Use of true-selectivity curve for prediction of interference.

sired signal voltage if the receiver is to continue to operate satisfactorily. Alternately, the transmitter frequency could be changed to f_{TX} and not cause any interference. As a second alternative, the distance *A* along the ordinate is the additional attenuation needed between the receiving and transmitting antennas if the interference due to the transmitter is to be removed. Thus, if the transmitter power output and the antenna types and spacing are known, the receiver guard band can be established.

The *True Selectivity Test* can be performed with various types of modulation on the interfering signal. These results are shown in Fig. 2-6 for 1000-cps unsquelched receiver noise, and randem noise, as the interfering signal-generator modulating voltage. All were adjusted for 20% modulation as indicated on a VU meter. The desensitization is fairly linear with noise-type modulations, but not with tone modulation.

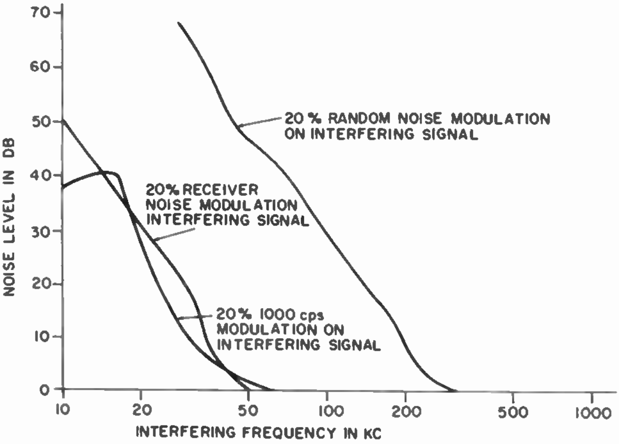


Fig. 2-6. Effect of modulation on true selectivity.

Band-limited noise modulation produces a transmitter spectrum very close to that of speech; therefore, the curves obtained using speech modulation should be very similar to those using noise modulation (Fig. 2-6).

FM Receivers—The FM receiver tests listed below are very similar to the AM receiver tests.

A. Desirable characteristics.
   1. Quieting-signal sensitivity.
   2. Weak-signal selectivity.
   3. Deviation sensitivity.

    4. Electrical fidelity.
    5. Signal/noise characteristics.
    6. Squelch sensitivity.
B. Interference Susceptibility.
    1. Co-channel.
    2. Susceptibility.
    3. Close channel.
    4. True selectivity.
    5. Impulse response.
C. Interference elimination.
    1. Spurious emissions.
    2. Conducted.
    3. Case radiation.

The six tests listed under *A* are standard IRE tests in most respects. They are performed to evaluate the desirable characteristics of the receiver and to provide a common basis for comparing different receivers. Of the remaining, only the true-selectivity test will be discussed in detail here. However, it should be observed that all of these tests are performed with a desired signal in the passband, as was done with the AM receiver tests. The arrangements for the FM receiver tests are similar to those for the AM receiver tests shown in Fig. 2-3, except that no dummy antenna is used.

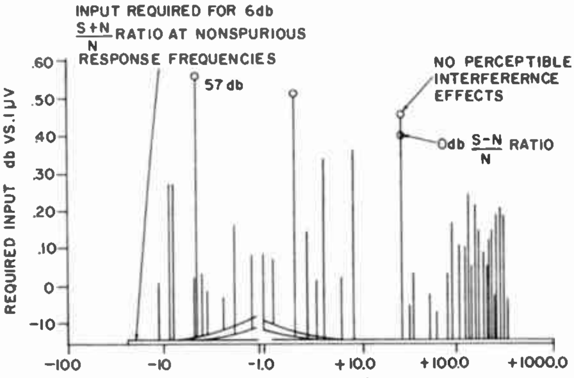


Fig. 2-7. Broad-band interference test.

Typical results of the true-selectivity receiver test are shown in Fig. 2-7. This curve is obtained in two parts because of FM receiver characteristics. The upper dotted points on the vertical lines represent the amount of desired signal necessary to negate all interference effects, while the solid curves are the desired signals necessary to produce a 6-db (S + N)/N ratio in the receiver output. It is necessary to do this because a given (S + N)/N ratio is difficult to obtain at a spurious response point. A 12- to 15-db reduction in the desired signal results in its complete capture at the spurious response points in most receivers; this is indicated by the lower point on the spurious responses.

The interference-free condition is thus related to the captured condition by a constant. The desired signal necessary to obtain a 6-db (S + N)/N ratio at the spurious response point can be found by subtracting approximately 6 db from the desired signal obtained in the manner described above.

Fig. 2-8 shows the response of a particular receiver over the range from 1 mc below the tuned frequency down to 150 kc, and from 1 mc above the tuned frequency up to 1000 mc. Due to the large number of spurious responses near the tuned frequency, those within ±1 mc on either side are expanded.

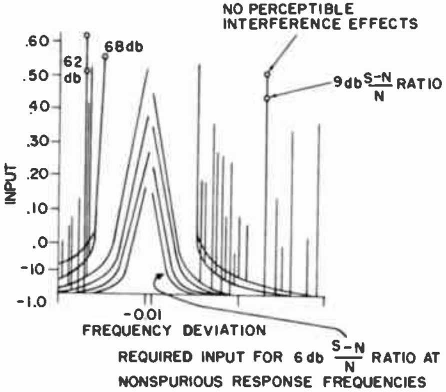


Fig. 2-8. Another broad-band interference test.

The results of applying different types of modulation will cause little or no deviation in test data because interference to FM receivers is largely indepedent of modulation, except in the co-channel test. The effects of different types of modulation of the interfering signal to the co-channel test are shown in Fig. 2-9. The output indicator is a distortion analyzer employing a VU meter.

The curve of Fig. 2-9 shows that the co-channel capture is relatively independent of the interfering signal modulation when the desired signal is weak; for strong desired signals, however, the capture slope is greater for modulations of any type.

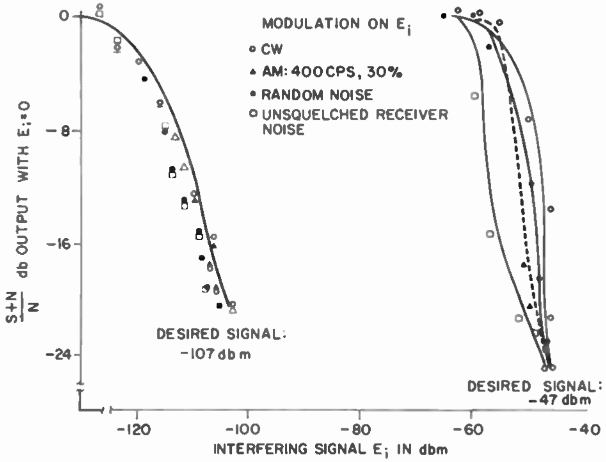


Fig. 2-9. Effect of modulation co-channel interference.

The AM and FM receiver tests indicated in the setup of Fig. 2-3 have been used with several receivers of different types, and accumulated sufficient data to show very definite trends. For example, the variation of spurious responses and magnitudes between two sets of the same type have been analyzed and probability density curves plotted, as shown in Fig. 2-10. These show the wide variation, from receiver to receiver, in the magnitudes of spurious response. When the spurious responses of two receivers are tested—first with their original tubes, then with the mixer tubes interchanged, and finally with the local-oscillator tubes interchanged—no significant change in magnitude was observed. Spurious-response magnitude variations, therefore, seem to depend primarily on

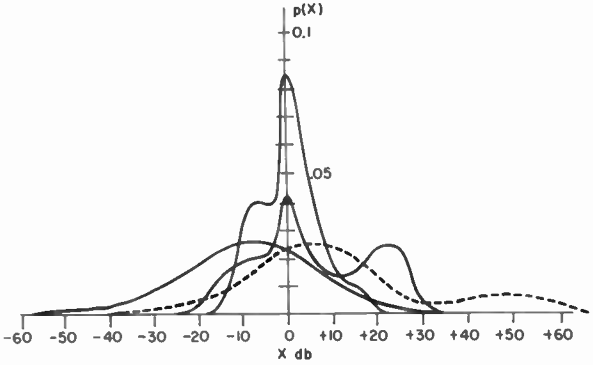


Fig. 2-10. Probability density function for the variation of spurious-response magnitudes.

variations in circuit components (other than tubes) such as lead dress and shielding. The wiring of these sets, when examined, was found to be completely different. The antenna lead completely encircled the mixer tube in the receiver having the lowest spurious-response rejection.

Transmitters—Transmitters are tested using procedures similar to those employed with receivers; however, no attempt to differentiate between AM and FM transmitters will be made here since the tests are identical.

A. Standard Tests.
    1. Spurious and harmonic output.
    2. Conducted (power leads).
    3. Intermodulation.
B. Characteristic Tests.
    1. Power output.
    2. Modulation bandwidth.
    3. Susceptibility.
    4. Modulation linearity.
    5. Carrier noise.
    6. Sideband splatter.
    7. Case radiation.

The block diagram for the test set-up used to evaluate spurious and harmonic emissions of transmitters is shown in Fig. 2-11. No rejection network is used to attenuate the transmitter carrier; laboratory tests have shown that it is unnecesary and often quite troublesome. The data obtained from this test on 14 transmitters, representing seven types, were normalized relative to the fundamental frequency and are shown graphically in Fig. 2-12. Indicated are k in db below the fundamental, the average and extreme values of harmonic emission

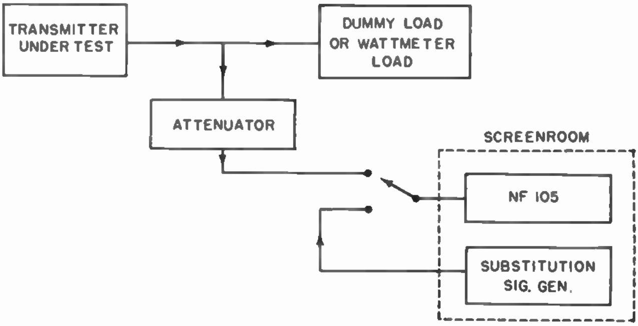


Fig. 2-11. Block diagram for power-output, spurious-emission and harmonic-emission tests.

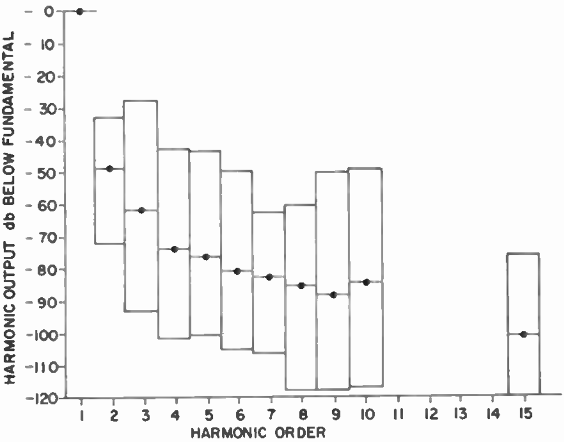


Fig. 2-12. Normalized harmonic emissions.

for each order, 1 through 10, and also for the 15th harmonic. The length of the rectangles represents the extreme variation of harmonic amplitude, normalized to the fundamental output. The dot near the center of each of these bars is the average level for a given harmonic. The variation in harmonic level from transmitter to transmitter, as well as between transmitter types, is quite large.

The test set-up used for the conducted interference, powerline susceptibility, modulation linearity, and modulator bandwidth tests is shown in Fig. 2-13. The harmonic interference conducted into the power line, measured in the conducted interference test, is shown in Fig. 2-14; these data are obtained

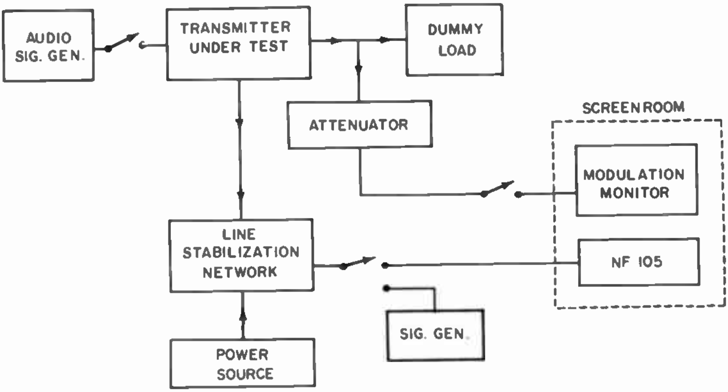


Fig. 2-13. Block diagram for conducted interference, susceptibility, modulator bandwidth, and modulator linearity tests.

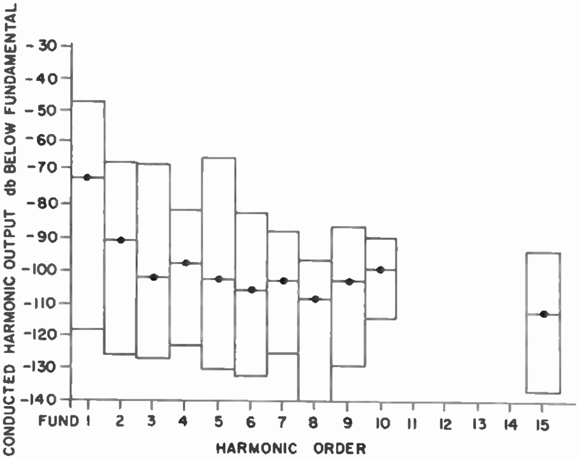


Fig. 2-14. Normalized conducted interference.

from the same equipment as the harmonic-emission data. Here, as in the harmonic-emission graph, the average and extreme values are plotted for each harmonic order. Observe that the ordinate is in db below the fundamental output power of the transmitter at the antenna terminals.

CHAPTER 3

Interference-Measuring Equipment

There are a number of instruments used for measuring RF interference at different frequencies. Generally, somewhat different techniques are required at low than at high frequencies because some methods will give satisfactory performance at low frequencies only.

The basic measuring instrument consists of a sensitive superheterodyne radio receiver and a calibrated RF noise generator capable of producing pulses of a precise amplitude-frequency characteristic at an adjustable repetition rate and intensity. The purpose of the RF noise (impulse) generator is to provide a stable, calibrated reference noise against which the intensity of the interference being measured is aurally compared. Interference is measured by adjusting the output of the receiver with its sensitivity control and a *slide-back* circuit, to a point at which the interference is barely audible (threshold level) in the headset. With the receiver so standardized, the output of the calibrated impulse generator is injected into the receiver and adjusted to produce this same level in the headset.

The value, in peak microvolts per kc of the interference being measured is equal to that of the calibrated noise-generator output. Since the receiver serves merely to amplify and detect both signals, the measurements are independent of receiver gain and bandwidth. The impulse noise generator utilizes no tuned or amplifying circuits and is, therefore, not subject to variations common to such circuitry. The absolute output of the impulse noise generator has been determined mathematically and confirmed by laboratory measurements with specially designed equipment.

The generator output is injected into the receiver in series with the antenna circuit. This permits measurements of the open-circuit antenna voltage independent of antenna impedance. The schematic and equivalent circuit of the input portion of a typical RF interference measuring set is shown in Fig. 3-1.

The receiver portion of the instrument, embodying numerous design features such as extensive shielding (and other measures necessary to avoid spurious responses), has a novel feature in addition to the input circuit just described. This is the slide-back circuit, which applies a variable (manually adjustable) bias voltage to the second-detector tube to form a "shelf" below which there is no response. Only pulses exceeding a preset value in amplitude produce a response in the receiver headset. This facilitates peak-value comparison of the interference being measured with the impulse generator output. It further serves to eliminate from the receiver output any fluctuation noise or ambient interference whose amplitude is below that of the interference being measured.

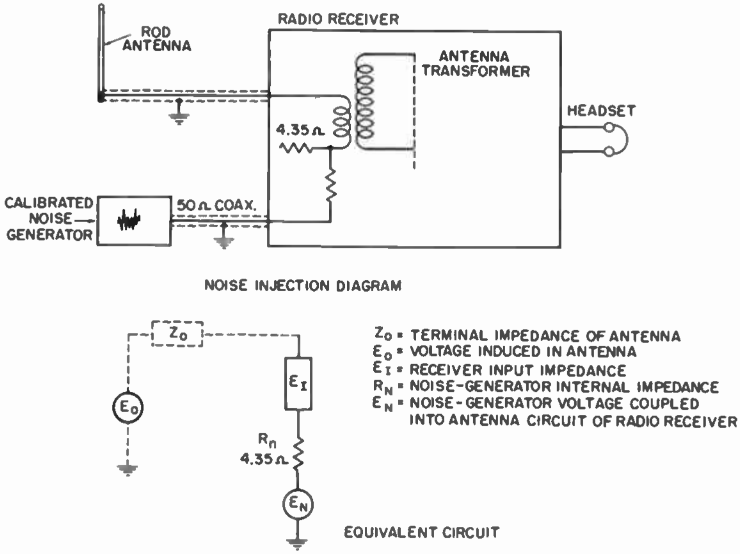


Fig. 3-1. Calibration circuit of interference measuring set.

Accessory equipment used with such an interference-measuring set includes a nine-foot whip antenna for radiated-interference measurements, magnetic and electric field probes for exploration and location of sources of interference plus conduction couplers and coupling networks for using the equipment as a two-terminal RF microvoltmeter for the measurement of conducted interference. A functional block diagram of such a set is shown in Fig. 3-2.

One typical interference-measuring set is used for detecting interference over the frequency range from 40 to 1000 mc and employs a modified radar receiver. The principal modifications of such a receiver, to make it suitable for interference measurement, are:

1. Peak response of the receiver, at its second detector, to interference impulses at its input is determinable by an aural null slide-back indicator which is indepedent of the pulse repetition rate.
2. The stability and linearity of the receiver are considerably improved.
3. The spurious responses between 300 and 1000 mc are greatly reduced.

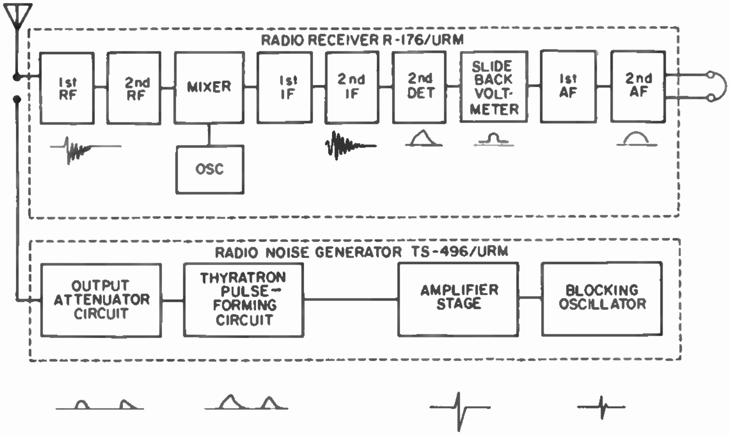


Fig. 3-2. Functional diagram of interference measuring set.

Such equipment measures interference directly in terms of db above 1 microvolt per megacycle, which is readily convertible to microvolts per megacycle or kilocycle. While this equipment does not incorporate an impulse noise generator, it can be calibrated in the laboratory by means of a standard impulse generator, the output spectral intensity of which is accurately known in terms of microvolts per unit bandwidth. Measurement of the peak value of impulse-type interference is made by an aural slide-back method.

The antenna used with this particular equipment is a special broad-band antenna requiring configuration changes at only three points throughout the frequency range from 40 to 1000 mc.

PICKUP DEVICES

One of the major problems of RF interference measurement is the selection of proper pickup devices. Those in general use consist of a short rod antenna, half-wave resonant dipole, and a three-inch shielded loop probe. The probe is used for locating points of leakage and possibly for making comparative measurements.

For this discussion, the types of radiating sources can be divided into three general classes. These consist of high- and low-impedance radiators, and complex sources containing both high- and low-impedance sources. Each type of radiator has been examined in Chapter 1 with respect to its effect on pickup devices. The merits of pickup devices can now be judged by their relative capabilities for detecting such sources, for the purpose of disclosing practical information on interference suppression. In addition there is a discussion on the ease of use and the repeatability of such measurements.

Rod Antenna

The rod antenna usually employed for measuring RF interference is 41 inches long, and is vertically polarized. Its impedance is approximately equal to that of a 10-mfd capacitor, varying from about 100,000 ohms at 150 kc to about 600 ohms at 25 mc. To match this antenna, the meter input circuitry must have high impedance too. Signals induced in the antenna by high-impedance radiators can be high in voltage and low in current.

Although the rod will also detect the electromotional component produced by low-impedance radiators, the energy contained therein is a small part of the total and leads to incorrect interpretation of the result. It is also true that accurate and repeatable measurements are very difficult to make with a rod antenna on this type of field. Directional effects are small when the rod is activated by quasi-static fields, but become quite important with electromotional electric fields. Hence, if the field is not vertically polarized, only part of the signal will be detected.

Loop Probe

The loop probe most generally used is three inches in diameter, electrically shielded, and has a single turn (although, at times, loops of two turns are used for low-frequency work). The loop must be placed near the signal source since it has comparatively low sensitivity.

The loop shield makes it quite insensitive to quasi-static electric fields of all frequencies at which the loop diameter is small compared with the wavelength. Measurements obtained with the loop antenna are good estimates of the magnetic-field magnitude. Positioning of the loop is important but presents little or no difficulty because of its small size and ease of handling.

For practical reasons, the loop should be used with 50-ohm coaxial cable which is terminated accurately in 50 ohms. Such a loop, of course, is not efficient at low frequencies, where it has a low impedance, but its sensitivity is satisfactory here.

Half-Wave Resonant Dipole

The dipole antenna is used for RF interference measurements between 30 and 1000 mc, since at lower frequencies its physical dimensions become too large for practical use. Sensitivity of the dipole is complex, being maximum at the center for low-impedance fields and maximum at the ends for high-impedance fields. Conversely, its sensitivity is minimum at the center and ends for high-impedance and low-impedance fields, respectively.

To make things more complicated, the impedance at the center is only moderately low. Thus, fairly good sensitivity is obtained to balanced, capacitively coupled quasi-static electric fields, as well as to electromotional electric fields which are properly polarized. The large size of the dipole over most of the frequency range dictates that it be used in a horizontal position. Because the dipole must be tuned for each measurement frequency, however, it is difficult and time consuming to use.

Comparison of RF Interference Pickup Effectiveness

RF limits for interference testing communications equipment are close to the background level of the measurement instrument. Comparison between the relative sensitivities of a well-designed noise meter using a sensitive antenna close to the source, and between a communications receiver provided with a shielded antenna cable, indicates far too stringent limits for use in most cases. If future methods of measurement are to permit relaxation of such stringent limits, the pickup device should give dependable measurements of the fields that can cause interference, while being insensitive to fields that cannot.

Low-Frequency Measurements (0.15 to 25 mc)—Since the dipole antenna cannot be used at low frequencies because of its size, only the loop and rod antennas need be compared.

Relative advantages and disadvantages of each antenna dictate that although the rod antenna is considerably superior to the loop for detecting signals from high-impedance sources, the relative importance of measurements with the rod antenna are questionable. This is because coupling of interference from high-impedance sources is not likely and if it does exist, the simplest measurements are adequate for its detection. If shielded lead-ins are used with all receivers, signals from high-impedance sources may be ignored completely.

Measurements made with the rod antenna on low-impedance sources are of questionable importance. In addition to the rod antenna being insensitive to the radiation, actual pickup is likely to result from a number of paths other than the rod, such as the ground plane, power lines, and other cables.

Measurements made of low-impedance sources with only the loop antenna give comparatively repeatable and accurate measurements which permit calculation of the suppression required to allow operation of the source near sensitive devices. This reliability of loop measurements results from the proximity of the loop to the source in the intense induction field, which usually falls off as the inverse cube or inverse square of the distance. Hence, the readings are independent of reflections or other external influences. The loop antenna is easy to handle and does not require tuning. Measurements made with the loop are very important because the type of signal of concern is capable of penetrating shielding, and is difficult to suppress.

When complex sources are being tested, ease of handling is moderate for both types of pickup devices because of the difficulty in locating the proper measurement point or points. The loop antenna has some advantage, however, because of its maneuverability and immunity to external sources. The ratings for repeatability and importance of measurement are the same as for the low-impedance sources discussed earlier.

High-frequency Measurements (25 to 1000 mc)—The dipole has only fair sensitivity for high-impedance radiators; the variation in impedance over its length permits a good match at the ends but comparatively poor match at the center. In addition, a null point exists at the exact center. For the same reasons, the dipole is poor for repeatability of measurements. Because of its requirements for tuning at each frequency, cumbersome size, and general sensitivity to external effects (reflections, body capacity, etc.) it is not easy to use. Little importance is attached to signals from high-impedance sources because shielded lead-ins are universally used. The loop antenna is insensitive to these signals and consequently does not indicate their presence.

Low-impedance sources can be measured with fairly repeatable results by use of a dipole if the setup is carefully standardized. Measurements made in a shielded room cannot be duplicated outside. If the polarization of the radiating source is unknown (possibly currents flowing at an angle from the surface of a transmitter), a true indication of the intensity will not be obtained and its maximum possible effect on sensitive equipment cannot be determined.

When several loop-antenna measurements are made of the same source, repeatable readings are obtained regardless of whether the test is conducted inside or outside a shielded room. Also, the loop, when properly positioned and oriented, gives a good estimate of the current flowing in a radiator. Comparison of this current with that in the loop used for making receiver susceptibility tests shows whether the source will cause interference in a well-designed receiver if located near a shielded antenna cable. This is probably the most important information obtainable about any interference source.

Dipole antenna measurements of a complex source are very difficult to carry out since the relative phase and position of high- and low-impedance radiators are completely unpredictable. Large indications can result from a well-located, intense high-impedance source, while under the same circumstances the low-impedance source may be of negligible output. Consequently, the importance of such an indication cannot be determined. Nevertheless, the loop antenna is superior to the dipole because it is maneuverable and does not require tuning. The sensitivity of the loop, with respect to low- and high-impedance fields, is good and poor, respectively, for reasons already discussed.

WHITE NOISE DEVICES

The inconsistencies of measurements performed with random noise generators indicates the need for a standard noise source with which other types of noise generators can be calibrated. A heated resistor can be used as a standard source of white noise, since the available noise power is proportional to the temperature of the resistor—a quantity which can be accurately measured.

The Generator

The generator and heater, shown in Fig. 3-3, consist of a coaxial termination and a pressurized type-N connector. The termination is heated by a coaxial graphite heater; the termination and heater are in a helium atmosphere. The particular heater configuration shown is chosen to minimize the magnetic field in the generator. Graphite is used because of its refractoriness and ease of fabrication.

The generator is designed for a 50-ohm impedance from 0 to 1000 mc. The termination which forms the generator consists of a coaxial transmission line with the outer conductor tapered. The resistive element is a uniform conductive film on a ceramic base. This film is sufficiently thin at the highest operating frequency of the generator so that its resistance has very little frequency dependence due to skin effect. (A 50-ohm resistor of special noise-source design does not suffer from skin effect at high frequencies.)

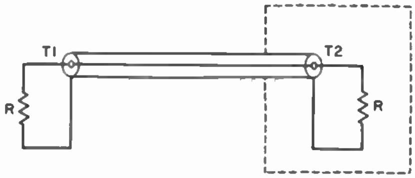


Fig. 3-3. Practical noise source.

The basis of the tapered design is the low-frequency lumped-circuit equivalent of such a termination. The measured impedance or standing-wave ratio of the termination at 1300°C is shown in Fig. 3-4; these measurements include the mismatch of the pressurized connector.

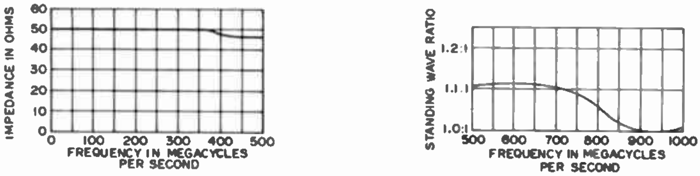


Fig. 3-4. Noise-generator impedance curves.

The Noise-Indicator

The noise-indicating instrument shown in Fig. 3-5 consists of spot-frequency amplifiers in the frequency range of 10 to 500 mc, followed by a bolometer-type power meter. The overall bandwidth (Fig. 3-6) is determined by a filter inserted in the first low-IF stage. Provision is made to balance the bolometer bridge by turning off the screen voltage of the first two low-IF stages.

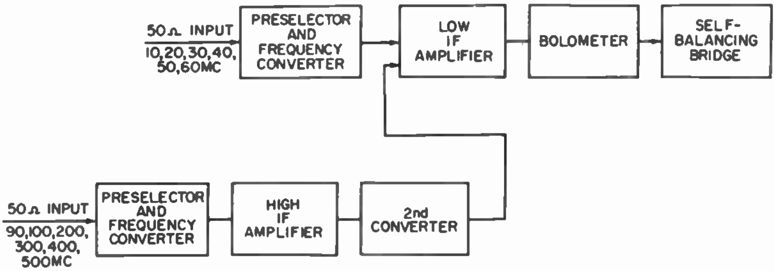


Fig. 3-5. Block diagram of noise measuring instrument.

The input impedance of the amplifiers is approximately 50 ohms. A circuit diagram of the 10-mc RF amplifier is shown in Fig. 3-7. The tuned-circuit elements in the 200- to 300-kc amplifiers (Fig. 3-8) are transmission lines. The over-all gain of the amplifiers provides a 10-dbm output at each frequency. A gain control provides means for adjusting the gain within a 15-db range.

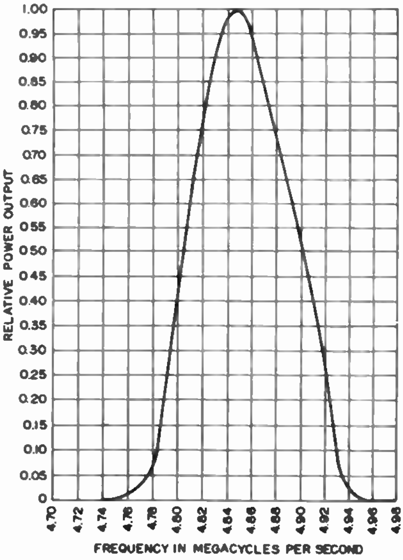


Fig. 3-6. Frequency response of noise measuring instrument.

MICROWAVE FIELD-INTENSITY METER

Below 1000 mc, an impulse generator with a spot frequency calibrator is usually employed for field-intensity measurements. The impulse generator is flat to at least a few hundred megacycles and, when used with a spot frequency calibrator, presents a good means of field-intensity calibration. This is particularly true with RF interference measurements, since broad-band interference is usually encountered.

Above 1000 mc, however, the impulse generator does not provide the appropriate interference calibration signal. Motor noise and sparking devices usually do not generate significant interference above 1000 mc. Most interference in this range is narrow-band; in addition, if an impulse generator were used for such measurements, the error introduced would be that of the impulse generator plus the absolute ouput of a spot frequency calibrator. This is true of all impulse generators, which are essentially relative-power devices. The error of the CW (continuous wave) calibrating generator must be included to obtain the absolute accuracy. The best method for microwave field-intensity measurements is a tracked CW calibrator adjusted with the receiver tuning control. The signal can thus be calibrated anywhere in the band, and operation will be the same on all tuning bands.

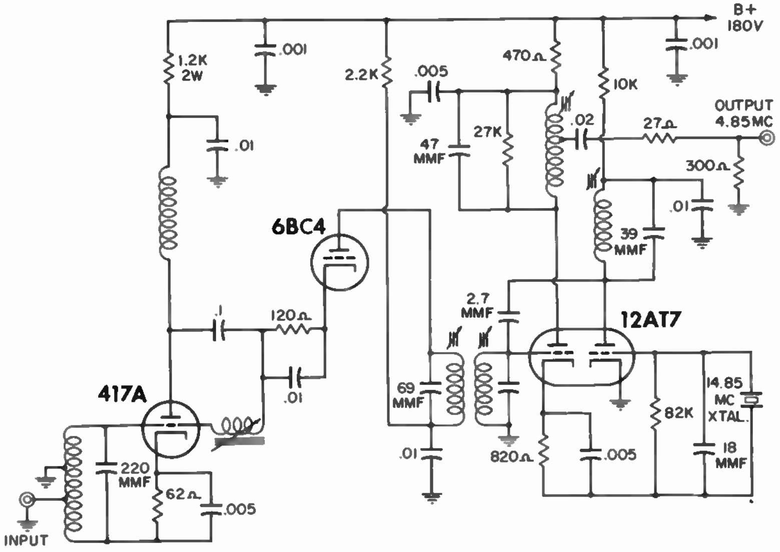
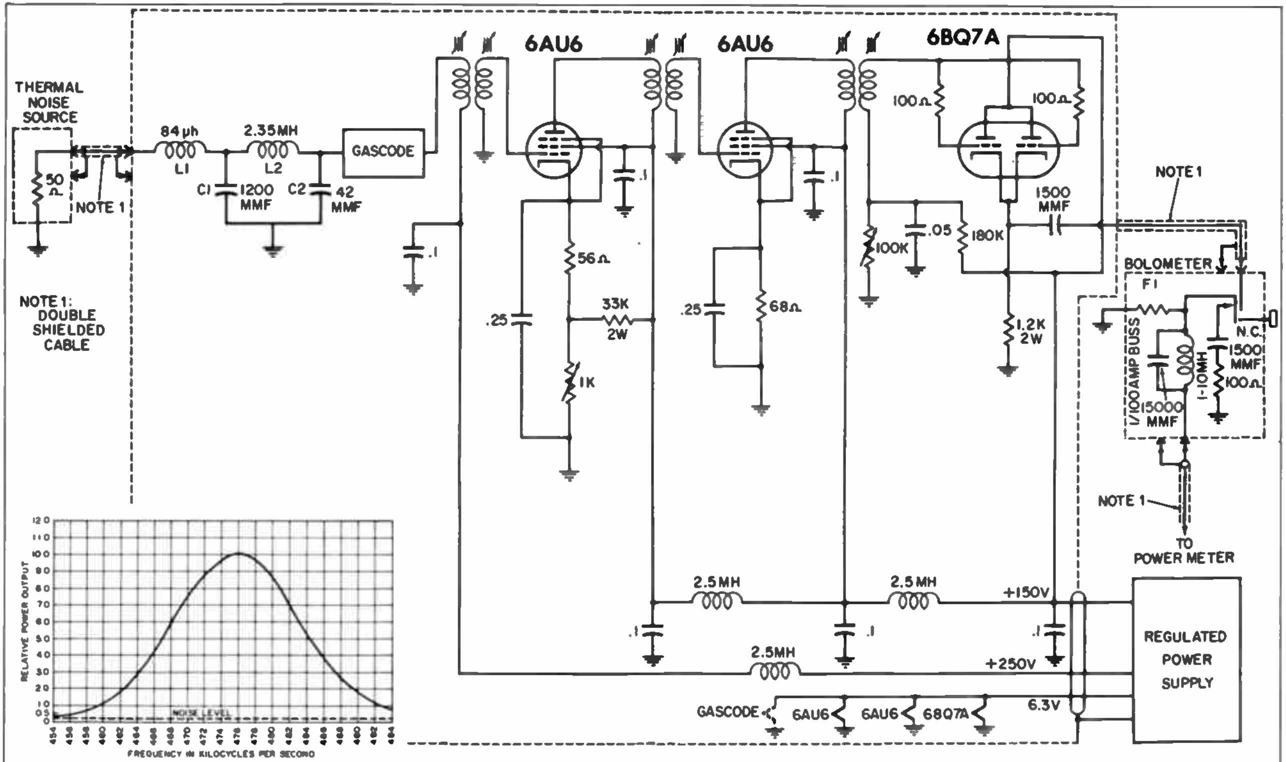


Fig. 3-7. 10-mc RF amplifier.

Continuous-Wave Calibrator

Fig. 3-9 shows the schematic of the CW tracked signal calibrator. Two coupling pipes are mounted to the oscillator cavity. The first is a conventional wave-guide beyond-cutoff attenuator calibrated from 0 to −100 dbm. The second pipe is an



(B) Frequency response.

(A) Circuit.

Fig. 3-8. 500-kc amplifier.

adjustable power unit containing a power-sensitive *thermistor*, which is part of a DC bridge circuit where the power is set at the 0-dbm level. The signal calibrator is essentially a laboratory-type generator.

The RF bandwidth is determined by the IF amplifier and is a compromise that provides good CW sensitivity, which requires narrow bandwidth and good pulse sensitivity. The latter, which requires a wide bandwidth, is necessary for high-frequency applications such as radar and missile guidance. Its bandwidth is 5 mc, which is sufficient for retaining a 0.015-microsecond rise time through the receiver.

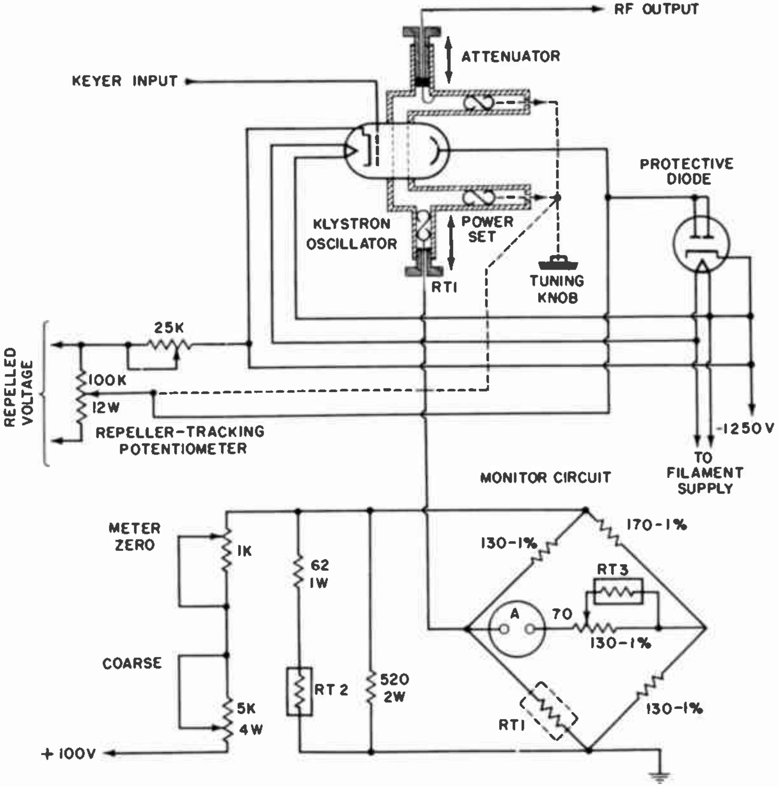


Fig. 3-9. Power monitor and signal calibrator.

The image frequency and other spurious responses should be attenuated to a level at which their addition to the true frequency will not appear on a full-scale meter reading. A two-cavity preselector is used because of its selectivity and image rejection. In addition, RF filters are added for higher-order harmonic suppression. Harmonic mixing of spurious responses and loop position attenuates unwanted signals 20 to 50 db. The filters supply additional rejection; spurious signals are down 60 db from any true signal received.

Measuring Circuits

The weighting circuits for this receiver contain average, quasi-peak, and peak time-constants. Peak measurements are made by a slide-back voltmeter. The time constants are 0.1 microsecond charge and 0.3-microsecond discharge for average and peak settings. A 50-microsecond charge and 600-microsecond discharge are used for the quasi-peak setting. The time constants are short because of the comparatively wide bandwidth of the receiver. Suitable biasing is supplied for proper meter-scale tracking. The VTVM used for monitoring signals coupled from the weighing circuits is a difference amplifier with a recorder circuit in series with the meter.

Antenna System

The antenna system for this microwave receiver is unconventional when compared with a dipole, rod, or loop antenna used with low-frequency devices. Two types of antennas are employed—an omnidirectional antenna to determine the presence of a signal, and separate band antennas (which have higher gain and are therefore more sensitive), for investigating lower field intensities. The latter are less susceptible to reflections because of their higher directivity. All antennas are linearly polarized. The directive antenna will deliver 20 microvolts in a field of 300 microvolts per meter. The omnidirectional antenna will deliver 20 microvolts to a 50-ohm impedance in a field of 4000 microvolts per meter.

Tuning

The tuning head contains the RF current attenuator, calibrated signal generator, local oscillator, preselector and mixer assembly, 260-mc preamplifier, and all of the required tuning mechanism. Other components are located in the monitor unit except the power supplies, which are in a separate chassis.

The signal is coupled from the preamplifier output to the monitor unit. The latter consists of the 40- and 140-mc IF strip, AFC chassis, crystal-controlled local oscillator, and all metering functions including the aural device.

The preselector design is based on the image-rejection requirements and mechanical backlash that will cause mistracking between the oscillator and preselector. The over-all bandwidth is about 10 mc at 2000 mc, and the RF bandwidth is five megacycles. Five megacycles is allowed for backlash mistracking and there is an allowed uncertainty of 1.5 mc to further reduce the effects of mechanical variables.

Capacity screens are used for tuning the preselectors of the low-frequency bands. Each cavity is independently tuned by a set of screens, which are active when the tuning plunger is directly under the associated alignment screw (used to align the preselector to the front-panel frequency dial). The mixer and mixer-to-preamp matching coupler are mounted to the preselector. The high-frequency heads contain mechanical tuning devices for making alignment adjustments. A mechanical tracking system is used for the preselectors of bands 3 and 4, because there is insufficient tuning to obtain sufficient capacitance range.

Characteristics most desirable for an oscillator are wide frequency range, continuous coverage, no tuning noise, and sufficient power for conversion. The external cavity klystron is used here because its characteristics come closest to meeting all these requirements. Four tuning heads cover the frequency range; the cavity length is proportional to wavelength. The drive cam linearizes the frequency by compensating for the hyperbolic function of the cavity. The same mechanism is used for the signal calibrator in each tuning head. *Teflon* bearings are used in the preselector mechanism and in the cavity.

Fig. 3-10 shows how the simple knob control in the tuning heads operates the preselector, frequency dial, tracking pots, and signal calibrator. Fine tuning of the signal calibrator is accomplished through a differential mechanism. The signal-calibrator output is available for susceptibility measurements, and a jack is provided on the front panel for external modulation.

Sufficient gain must be provided in the IF system to amplify noise (or signal) for operation in the linear region of the final detector. About 120 db is required, since the sensitivity of the IF system is about 2 microvolts. A multiconversion system is used because any significant amount of gain at the first IF of 260 mc can be difficult (and expensive) to achieve. Another problem in designing high gain at a single frequency is regeneration at the intermediate frequency. For these reasons, where the intermediate frequencies are 260 mc, 140 mc, and 40 mc, a triple-conversion system is used for the microwave field-intensity meter.

The RF bandwidth is about 0.05% of the operating frequency at the high end of the band. A drift of 0.25% will therefore cause a 6-db loss of signal when the unit is tuned exactly to the center of response. Since the receiver can conceivably be used to monitor signals for long periods of time, automatic frequency control is a necessary function. The AFC system is coupled from the last 40-mc amplifier to an amplifier and limiter circuit. The Round-Travis discriminator is isolated from ground because the DC output is coupled directly to a DC amplifier which varies the klystron reflector voltage. This will vary the frequency in a direction that compensates for signal or local-oscillator drift. The pull-out range is from 10 to 20 mc, depending on the tuning head in use.

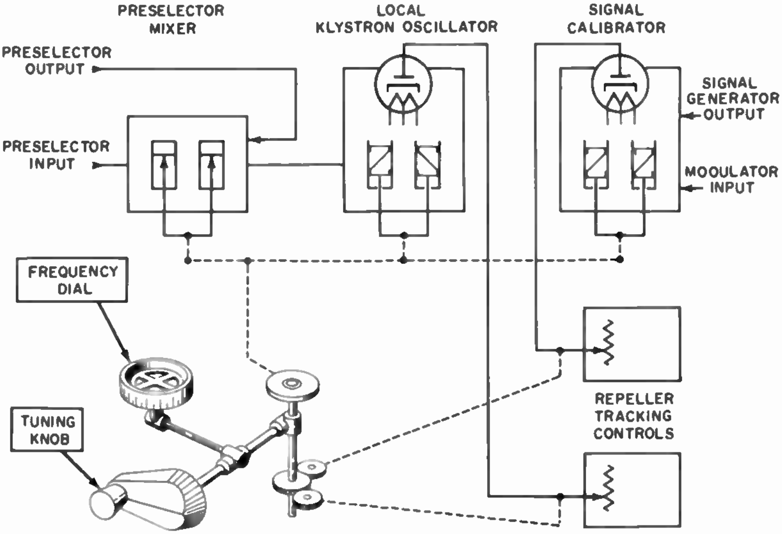


Fig. 3-10. Single-knob control mechanism.

The field coupled to the antenna may be specified in field intensity per unit length (volts per meter) or in power density per unit area (watts per square meter). The latter is the more convenient term to use at microwave frequencies, because power delivered to the receiver is independent of the impedance level; in addition, the effective area is a commonly used antenna characteristic.

CHAPTER 4

Measurement Problems

The problems associated with RF interference measurements are many and varied, especially those encountered in tests to determine the intensity of the electromagnetic field which surrounds the interference source.

Some interference measurement problems are due to the particular class of equipment being tested and the environment in which it is used. Test items such as vehicles used in the open and some distance from sensitive electronic equipment present a different set of problems from items to be installed near a large amount of electronic equipment. Although this chapter is concerned primarily with the difficulties encountered in the latter installation, a major portion will be of a general nature and will apply to all interference measurements. Since the over-all problem is of considerable complexity, the discussion is broken down into three parts: the RF interference field, the antenna system, and the correlation of meters.

THE RF INTERFERENCE FIELD

In order to obtain similar measurements of radiated interference under different circumstances, it is necessary that the RF interference field be controlled so the same general field intensity and contour are produced. Ambient RF interference levels are almost always too high to permit accurate measurement without a shielded enclosure unless an isolated open area where there are no interfering sources (within established limits) can be found. In addition, when a shielded room is employed, the position of the equipment under test and the position and orientation of the pickup antenna are generally specified. Fig. 4-1 shows a top view of the general test set-up; as shown, the dipole is always positioned horizontally, while the rod antenna is positioned vertically.

Installation of standard impedance networks in all power leads permits accurate and repeatable measurements of conducted interference and also provides control of radiated interference emitted by such leads. In this manner, the field contour, and consequently its effect on the pickup antenna, are controlled as much as possible. However, variables which cause disagreement between one interference-measuring facility and another will still exist. These variables include such things as differences in shielded room dimensions, location of metallic objects within the room, and the location and number of observers. In the higher frequency ranges, minor changes in physical relationships can produce large changes in measurements. A more detailed discussion of further difficulties requires that the general problem be further broken down into two distinct frequency ranges, each having its own peculiar set of problems.

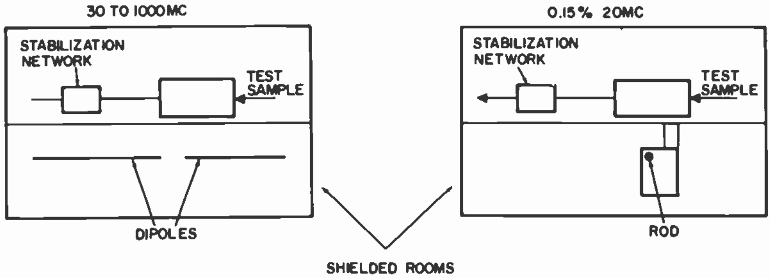


Fig. 4-1. General test setup.

Field Problems in the 0.15- to 20-mc Range

In the 0.15- to 20-mc range, the pickup antenna is a 41-inch non-resonant rod operating into a high-impedance meter which measures, in microvolts, the amount of signal induced in the rod. This provides a comparatively simple and dependable method of measurement; however, certain defects must be pointed out. The 41-inch rod is a high-impedance antenna which is sensitive to high-impedance fields but insensitive to low-impedance fields. Consequently, if the.radiating source of the interference happens to be a short open-ended wire, a panel jack, or any other high-impedance device, a large voltage can be built up with very little current flow. The induction field thus created has practically all of its energy in the electric component, with highly effective coupling. Conversely, if the radiating source were a short grounded wire, the outer surface of a shielded cable, the metallic surface of an equipment case, or any other low-impedance source on which large currents can be made to flow with little generation of voltage, the resultant induction field would be primarily magnetic, with poor coupling of energy to the 41-inch rod.

Obviously, the rod antenna provides control only over the electric component of the induction field, and is effective for the measurement of interference which would enter electronic equipment through high-impedance points such as an open-wire antenna lead-in. Very little measurement is made of interference which would affect such points of entry as loop antennas on low-frequency direction finders.

Measurements of the magnetic source at frequencies above 30 mc are performed with the dipole antenna. Shielding the electronic component, to the extent of passing the 41-inch rod-antenna limits, is a comparatively simple procedure, but this may still leave large currents flowing on the surface of the cases and interconnecting cable shielding. If the interference is broad-band, such as radar modulation pulses, these currents will be detected by the dipole antenna. Sources which seem to produce little or no interference when tested with a rod antenna exceed considerably the permissible limits when measured with the dipole. Thus, the rod and dipole antennas are sensitive to different types of fields and there is little or no correlation between measurements made with them.

While the electric field has been considered only from the quasi-static or presence-of-charge viewpoint, an electronic field-component may also be generated by the acceleration of charges. The two sources of electromotive force may be compared, respectively, to the voltage induced in one capacitor plate by a charge contained in another, and to the voltage induced in a transformer secondary by a (time rate) change of current flowing in the primary. Disregarding the two sources of electric fields sometimes leads to apparently contradictory situations. Suppose, for instance, rod-antenna measurements are being made on an open wire between two units and the wire happens to be terminated at each end in a high impedance. Application of a moderately sized capacitor at any point on the line would effectively load down any RF interference voltages on the line, and greatly reduce the rod-antenna pickup. The diagram of Fig. 4-2 demonstrates a simple condition, two units connected by a single unshielded lead. (Actual conditions may involve 20 or more leads.)

If, on the other hand, the line were terminated at each end in low impedances and the electric component were produced by the current flowing in the line, addition of the capacitor at the load end of the line would only increase the current, with a corresponding increase in the reading obtained using the rod antenna. Peculiar results such as this also can occur when the capacitor resonates with the inductance of the line. Generally, while interference on the high-impedance leads may be suppressed effectively by application of capacitors, low-impedance leads are best suppressed by application of a pi-section filter placed as close as possible to the point where the interference voltage is being generated.

Another case where peculiar results may be obtained because of a low-impedance field is in measurement of a high-intensity, broad-band magnetic source with the rod antenna and an interference meter. The effect is the same as when the meter attenuator is increased to bring the reading on scale; a point will be reached where further increase in attenuation will no longer have any effect on the reading. This is caused by currents induced in the metallic surfaces of the meter. These currents penetrate the openings and seams, causing voltages to be induced in the IF stages and thus bypass the attenuator. Correction is obtained by building a secondary shield around the entire measuring instrument, with copper wire screening, leaving only small openings for the rod antenna and operation of the tuning and calibrating knobs. This is a common difficulty; almost all interference measuring meters are deficient in shielding for low-impedance fields.

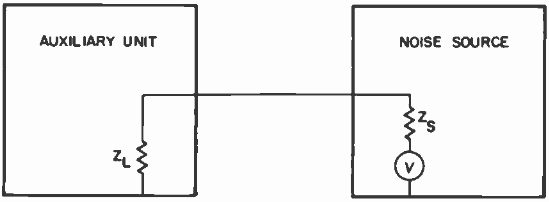


Fig. 4-2. Typical noise problem.

Problems in the 20- to 1000-mc Range

Measurements in the 20- to 1000-mc range are usually made with a resonant dipole antenna. Distances between the interference source and the antenna, shielded-room dimensions, cable lengths, etc., that become comparable to the wavelength and interference fields of moderate impedance are the rule.

Reflections become troublesome from 60 to 300 mc, where large variations in measurements result from small changes in physical relationships. After tuning the antenna and calibrating the meter, the observer should move about in the shielded enclosure while maintaining a distance of at least three feet from the antenna; and the maximum readings obtained should be recorded. It is important that the meter be well grounded to the copper ground plane. This is necessary to minimize hand-capacity effects and other variations during tuning and calibration.

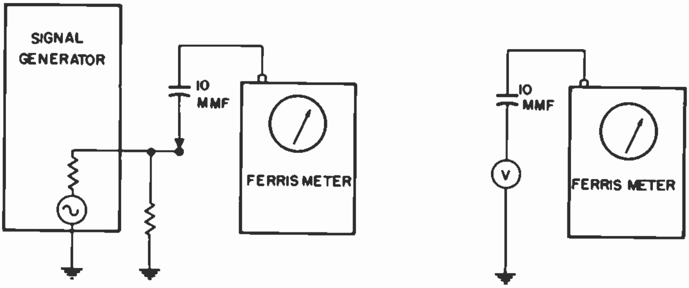
A particular case where unusual difficulties might be encountered in this frequency range occurs when both the antenna and meter are exposed to very high-intensity fields. Invariably, enough of the field penetrates through the seams of the meter to induce signals in the IF stages, and these signals are comparable in strength to those arriving from the antenna circuits and attenuator. Since the phase relationship between the signals arriving from the different paths can assume any value, highly erratic results will be obtained. Inside a shielded room such a condition can be corrected by making connection to the external antenna through coaxial cables and fittings in the shielded-room wall. Almost every RF-interference and field-intensity meter available is inadequately shielded for high-intensity field-strength measurements.

ANTENNA SYSTEMS

The amount of energy transferred from the field to the interference-meter input terminals is a function of the antenna length, impedance, location, and orientation. Also, it may vary with the type of transmission line used, if any, and the input impedance of the meter. Standard RF-interference limits, independent of any particular meter, are provided in terms of the open-circuit voltage induced in a 41-inch rod antenna. The meter is connected in series with a 10-mmf capacitor and a known voltage source during calibration. The 10-mmf capacitor is equivalent to the antenna impedance. Also, the voltage source (probably a 50-ohm signal generator) has insignificant impedance compared with that of the capacitor and the input impedance of the meter. Therefore, the open-circuit generator voltage is not loaded down and the noise-meter gain may be adjusted to read the same value as the known generator output voltage. The meter is then switched to its internal calibration source, usually a noise diode, and the reading recorded.

Theoretically, the meter gain can now be adjusted to this same value at any time in the future by switching on the internal calibrator and adjusting the gain control. If the output meter tracks properly, it may be used as a high-impedance microvoltmeter. When the rod antenna is substituted for the 10-mmf capacitor, any induced voltage will be read directly by the meter, since the circuit impedance is essentially the same as during calibration. Fig. 4-3A represents the low-frequency meter calibration; Fig. 4-3B represents the equivalent circuit when the rod is in use.

In the VHF and UHF ranges, the standard antenna is the resonant dipole. In order to determine whether a given interference measurement is within desired limits, it is necessary to relate the antenna standard limit to the actual reading observed on an interference meter which has been coupled to the antenna. The portion of the induced voltage appearing across the input of the meter is a function of the antenna and meter impedances (assuming that all cables are correctly terminated at the receiver).



(A) Calibration set-up.

(B) Equivalent circuit (with rod antenna in use).

Fig. 4-3. Low-frequency meter.

Since all meters do not have the same input impedance, the input voltage, which corresponds to a given limit in microvolts, induced in the antenna will differ from meter to meter. To simplify their use, the standards are broken down into input-microvolt limits for each type. All calculations, in such a derivation of limits, assume a dipole-antenna impedance of 72 ohms. Inaccuracies will result when the dipole impedance departs from this value; however, this will produce inaccurate calculation of induced antenna microvolts, but will have little effect on the comparative measurements.

As a result, the relative ability of the various meters to impose the same restrictions in the RF-interference measurements of electrical or electronic equipment will remain essentially unchanged. Variations of antenna impedance between 20 and 100 ohms produce maximum inaccuracies in meter correlation of less than 10%.

METER CORRELATION

While minor discrepancies are found in the correlation of measurements made with various types of field-intensity meters, results are generally satisfactory and far exceed the accuracy of broad-band interference-measurement correlation. Consideration is given here only to the cause of inaccuracy in broad-band correlations.

All broad-band interference may be considered to be impulsive in nature, and the energy which such interference enters the input circuits of a receiver is directly proportional to the average bandwidth. This is not strictly true for such interference as that from a commutator or fluorescent light; however, test results indicate that reasonably good correlation is obtained using this assumption. Impulse-type interference sources emit energy which is spread out over a comparatively large frequency spectrum. The receiver samples a portion of this spectrum near the frequency to which it is tuned.

A number of impulse generators which simulate impulse interference have been developed especially for improving the broad-band interference measurement accuracy. A good example is the IG-102 impulse generator developed at Purdue University and manufactured by Empire Devices, Inc., Bayside, New York.

The output of the IG-102 consists of repetitive impulses, similar to those obtained from ignition interference, having a maximum amplitude of approximately 150 volts and a duration of 0.0005 micro-second. The repetition rate may be varied between 2.5 and 2500 pulses per second. In contrast to ignition interference, which has a large energy content in the lower-frequency ranges and decreases rapidly in the VHF range, the energy content of the impulse is constant from audio frequencies up to 1000 mc. Fig. 4-4 shows the duration of the impulse must be less than or equal to the duration of one-half the sine wave in question to maintain a flat-top characteristic.

Consider a single-stage RF amplifier resonant at some frequency below 1000 mc. To avoid confusion in this discussion, the signal emitted by interference sources or generators will be called impulses and the resultant receiver output signal will be called pulses. The duration of the impulse, 0.0005 micro-second, would be only a small fraction of the time required for a single cycle of amplifier oscillation. Application of the impulse would suddenly charge the tuned RF-circuit capacitor to a value depending directly on the available energy. The circuit would then proceed to oscillate until all the energy was dissipated in the resistance of the circuit. For a given amount of reactance, if the resistance were high, the Q of the circuit would be low and the energy would rapidly be dissipated. If the resistance were low, however, the Q would be high and the circuit would oscillate for a comparatively long time. Since the bandwidth of the circuit is inversely proportional to the Q, the duration of the oscillations becomes greater as the bandwidth decreases, and vice versa.

If the initial pulse is now considered, from the viewpoint of its component Fourier harmonic frequencies, the only portion of the impulse energy contributing to the oscillations is contained in the harmonics which lie within the passband of the amplifier. Increasing or decreasing the bandwidth will include more or fewer harmonics. This increase or decrease in the available energy content results in a corresponding increase or decrease in the peak amplitude of the input signal. If the signal is fed to a suitable detector which reproduces the envelope of the RF oscillations, the output pulse will have a peak amplitude directly proportional and a duration inversely proportional to the amplifier bandwidth. Since the pulse duration and shape are a direct result of the RF amplifier they have no relationship to the duration and shape of the original interference impulse which injected the energy into the amplifier. The output pulse obtained with ignition interference would be the same size and shape as that obtained with the IG-102 impulse generator or any other source of impulse noise, provided only that they inject the same initial amount of energy into the RF amplifier.

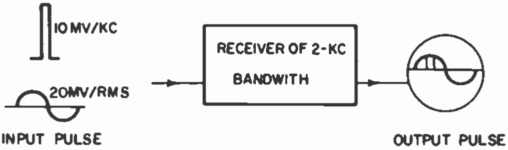


Fig. 4-4. Microvolt per kilocycle bandwidth.

Thus, the original interference impulse may be of any shape and amplitude and still have the same ability to cause RF interference at a particular frequency. Since the amount of energy the amplifier picks up is directly proportional to its bandwidth, variations in bandwidth will give proportionate variations in measurements. Doubling the receiver bandwidth doubles the energy in the receiver output pulse (Fig. 4-5). Thus, twice the energy is picked up from the broad-band interference spectrum.

Expression of the interference in terms of microvolts per unit bandwidth makes the measurement independent of bandwidth variations. By definition, the rms sine-wave input (in microvolts) required to produce, at the second detector, a peak amplitude sine wave equal to that produced by an impulse signal is equal to the impulse in microvolts per unit bandwidth times the bandwidth of the receiver (in the same units). For example, if a 10-microvolt-per-kc-bandwidth signal were applied to a meter with a 2-kc bandwidth, the pulse that appeared at the second detector would have a peak amplitude equal to that of the sine wave which would appear there if a 20-microvolt sinewave were applied. Fig. 4-4 is a pictorial representation of this definition of microvolts per kc bandwidth.

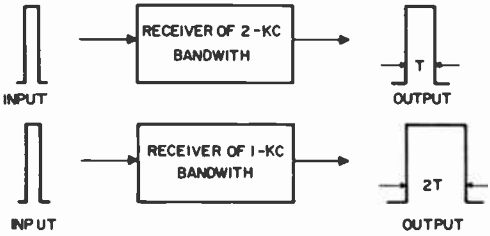


Fig. 4-5. Relationships of pulse energy.

Bandwidths may be measured approximately with sine-wave signal generators by determining the frequencies at which the second-detector voltage is down six decibels on each side of the center frequency. Present practice is to measure, with impulse generators, the bandwidths of the most accurate meters available. Then comparative measurements of interference sources are made and correction factors obtained for the less accurate meters. All meters which are incapable of measuring the peak amplitude of the pulse at the second detector will then require comparative measurements.

CHAPTER 5

Electrical-Circuit Noise

Electrical circuit noise becomes a problem when there is a source of noise, either steady state or transient; there is a way for the noise to get into the circuit, either by direct connection or by electrostatic or electromagnetic coupling; and when the circuit is capable of malfunctioning because of the noise.

RF interference generated by electronic equipment usually originates in resonant circuits or is caused by switching action. Thyratrons are one of the most important electronic devices used for switching. The resonant circuits producing interference are combinations of elements used specifically because of their resonance or those which cause accidental resonances. The first group includes transmitters, modulators, and local oscillators in receivers. The second group includes primarily amplifiers as well as almost all other vacuum tube or semiconductor devices.

Oscillations may occur in electrical systems whenever the circuit elements are so connected that electrical energy may be exchanged between them periodically. The most common example is the combination of a capacitance, which is capable of storing electrostatic energy, and an inductance, which can store electromagnetic energy. Oscillations in such systems, once started, would continue indefinitely if there were no resistance in the circuit. All actual circuits contain resistance, however, and sustained oscillations consequently require a power source such as a vacuum tube to replenish the energy dissipated in the resistance.

The RF interference generated by such electronic devices, except that generated by thyratrons, has a common characteristic—almost always a single frequency, or at most only a few frequencies, are generated. This is continuous-wave (CW) interference compared to the "broad-band" interference, which is generated by ignition systems and rotating machinery, and covers a very wide band of frequencies. Although such interference is restricted to only a few frequencies, its magnitude is much greater at these frequencies than that usually caused by other types of sources. These two factors must be taken into consideration in the design of any interference-suppression system.

TRANSMITTERS

Radio transmitters are generators of RF energy which is controlled by the intelligence being transmitted. Obviously, the energy radiated at the transmitter frequency cannot be considered as RF interference. The interference associated with transmitters is the energy radiated at other than the operating frequencies. Because the antenna of a transmitter is designed specifically to be an effective radiator, any undesired energy entering it will be radiated and result in very strong RF interference. Even when the undesired energy does not reach the antenna, a considerable amount may escape, through conduction and radiation, from the wiring and other parts because of the high power involved.

The frequencies at which transmitters generate interference are almost always in the immediate vicinity of the operating frequency, harmonics, or subharmonics of it. In the first, the cause is an unstable oscillator; in the second and third, a poor waveform. Nevertheless, suppression measures applied to completed equipment are usually unsatisfactory; RF interference should be considered during design.

Extensive shielding of all component parts and all interconnecting wiring, together with installation of adequate filters in all power and control leads, will eliminate all interference except that radiated by the antenna. It obviously cannot be shielded, but a set of specially designed harmonic-suppression filters in its input circuit will eliminate all interference except that radiated in the immediate vicinity of the operating frequency. Such an installation, however, could be extremely bulky and expensive.

The suppression measures that should be designed into all transmitters are high oscillator stability and low distortion. The first is usually achieved by using a crystal-controlled oscillator or, when this is not feasible, high-precision tuning elements; and by inserting one or more buffer stages between the oscillator and power amplifier to keep the oscillator circuit as free from loading as possible. Distortion is kept to a minimum by avoiding overloads on all tubes and by extensive use of negative feedback. Finally, a low-pass filter whose cutoff frequency is about midway between the fundamental and second harmonic may be incorporated in the transmitter output circuit.

MODULATORS

Modulators such as those in radar transmitters produce very large amounts of pulse energy usually having fundamental frequencies below 10 kc and therefore too low to be considered RF interference. Since square and other non-sinusoidal waves are produced, however, the large number of harmonics generated together with the fundamental can produce severe interference at all radio frequencies.

Modulators are usually integral parts of radar transmitters. Extensive shielding of the entire unit and all interconnecting wiring is an absolute necessity. Feedthrough capacitors or filters are a big help, except in some designs. A typical installation which makes extensive use of shielding is shown in Fig. 5-1. Individual shields are used on the primary power leads, from the transformers to the point where the leads leave the modulator case. This shielding consists of a solid copper tubing

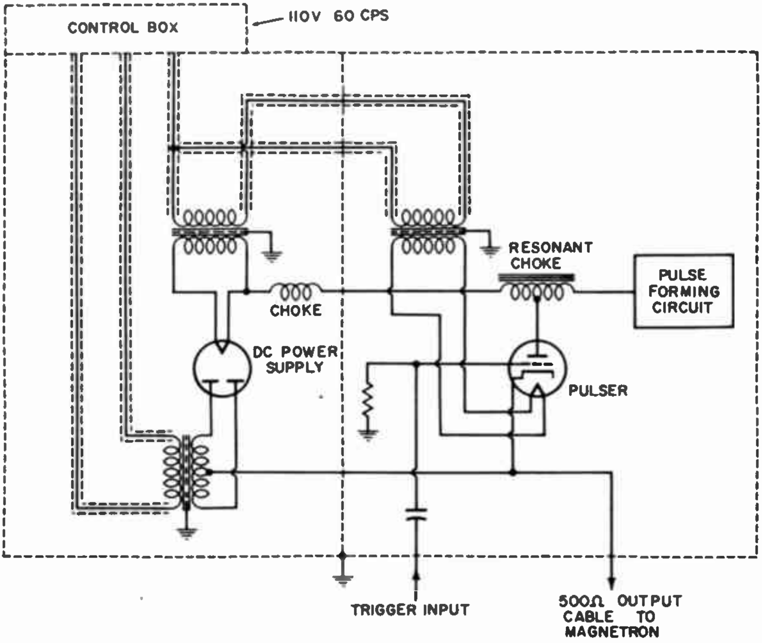


Fig. 5-1. Shielding of a radar modulator.

which is properly grounded. In addition, solid copper sheets are used as electrostatic shields between the primary and secondary windings of the power and filament transformers.

The circuit shown in Fig. 5-2 makes extensive use of feedthrough capacitors, and shielding is kept to a minimum. This type of installation is preferred because of its lighter weight and greater economy.

LOCAL OSCILLATORS

Local oscillators are used in superheterodyne receivers to supply a signal that is mixed with the incoming signal to produce an intermediate-frequency output. The local oscillator thus performs an essential function, and its oscillations cannot be eliminated. They can, however, be prevented from being conducted along the receiver wiring and radiated.

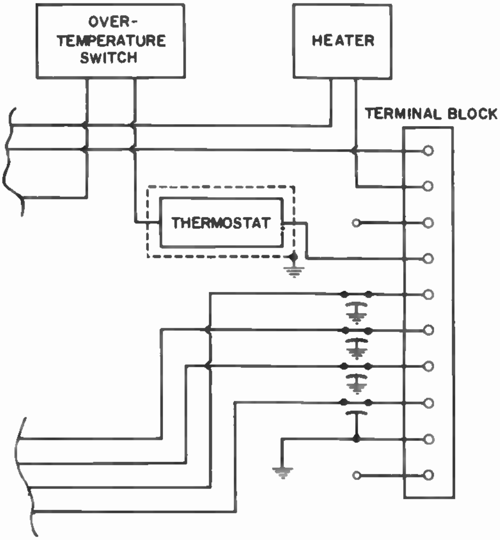


Fig. 5-2. A portion of a radar installation diagram.

Both radiation and conduction of local-oscillator energy is best eliminated by proper design. A poorly designed receiver is very difficult to suppress—particularly if most of the undesired radiation escapes through the antenna, which obviously cannot be shielded.

Conducted interference from local oscillators is rarely a problem because stray coupling between the oscillator and power circuits is easily prevented. Radiation is much harder to suppress; most oscillator radiation is either from the antenna or chassis. Both can be eliminated only by redesigning the circuit.

If the receiver chassis is radiating local-oscillator energy, poor location of grounding points is frequently responsible. Shifting the points at which the oscillator grounding connections are soldered to the chassis is sometimes effective. In extreme cases, complete shielding must be employed.

If, as is most common, the local-oscillator energy is radiated by the antenna, then shielding is not feasible. For a receiver operating on a fixed frequency, a band-elimination filter can be inserted into the antenna circuit. Most receivers are tunable over a wide band of frequencies, however, and this is not practical.

Fig. 5-3 shows a block diagram of a superheterodyne receiver. An RF amplifier, between the antenna and mixer, is universally used at frequencies below about 50 mc except on lower-priced models. Since an electronic amplifier acts like a one-way valve, such a stage of amplification is one of the most effective methods of preventing local-oscillator energy from reaching the antenna. This RF stage is sometimes omitted in receivers operated at VHF and UHF frequencies. But it is these receivers, in which the antenna circuit feeds directly into the mixer, that are most likely to radiate RF interference. The only effective suppression under these circumstances is to turn off the receiver.

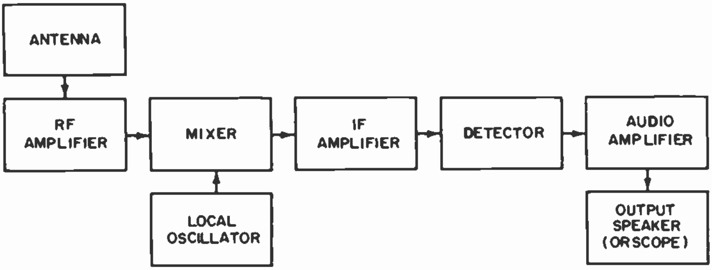


Fig. 5-3. Block diagram of a superheterodyne receiver.

Design features that help reduce or eliminate local-oscillator interference include proper internal shielding of the oscillator and mixer stages, use of electrostatic shields in coupling transformers, careful routing of wiring, and high antenna-circuit selectivity. The choice of intermediate frequency should be determined, in part, by the possibility of its radiation and possible effect on other equipment.

PARASITIC OSCILLATIONS

Parasitic oscillations are those which occur at other than desired frequencies, or in any circuit not specifically designed as an oscillating circuit. They occur primarily in oscillators and amplifiers, but may occur in almost any other electronic circuit.

In addition to RF interference, spurious frequencies resulting from parasitic oscillations may cause distortion in linear amplifiers and modulators, undesired sidebands in transmitter output signals, flashover, and reduction of useful power output. Because of these and other undesirable effects, parasitic oscillations should not be allowed to occur in well-designed electronic equipment.

Occasionally, parasitic oscillations occur that are so weak, they are not noticeable until a check for RF interference is made. Since such checks are made with sensitive radio receivers, very weak disturbances can be detected which may nevertheless seriously interfere with radiocommunications.

When it becomes necessary to suppress RF interference resulting from a parasitic oscillation, the first step is to locate the offending circuit. This is achieved through trial and error, by the process of elimination. When the cause has been located, the oscillations can usually be stopped by slight modifications which do not affect normal circuit operation. Often the insertion of a resistor of 1 to 25 ohms in series with the grid or plate lead of the tube in the offending circuit is sufficient. Sometimes the cause is a stray resonance between a RF choke and either its own distributed capacitance or some other capacitance in the circuit. In such a case, substitution of another choke with somewhat different inductance, or insertion of a small resistor in series with the choke, will eliminate the parasitics. Sometimes a slight detuning of certain elements, not enough to affect normal operation, is effective.

MEDICAL DEVICES

Diathermy and certain other medical equipment are essentially radio transmitters. When they were first used, this fact was not fully realized. As a result, many installations were very serious sources of RF interference. However, in 1949 a set of FCC regulations went into effect. These regulations, established to end such RF interference, made illegal after June 30, 1952 the use of nonconforming equipment. They are based on the recognition of these medical devices and similar equipment as transmitters. Definite frequencies are assigned to these devices, in a band not used for communications, and very stringent limits concerning the energy that may be radiated or conducted at other frequencies have been established.

Manufacturers have found it possible to conform to these regulations by using crystal-controlled oscillators and linear output circuits to keep the waveforms sinusoidal. Operation of equipment manufactured before this regulation and which does not conform to the FCC regulations must be operated within a properly designed shielded enclosure containing well-fitted electrical connections so that no interference can escape through control wiring or power lines.

Part 18 of the FCC *Rules and Regulations* (governing the operation of medical diathermy equipment) should be consulted for specific details regarding the design and operation of such equipment.

THYRATRONS

A thyratron is a hot-cathode gas-discharge tube in which one or more electrodes are employed to control the starting of the current flow. Essentially, thyratrons act like relays since a small amount of energy in the grid circuit controls a large amount of energy in the plate circuit.

Thyratrons are frequently used in circuits for their relay action. But because of their short response time, they are particularly useful in applications requiring rapid repetitions of relay actions, such as in pulsing circuits. They are also frequently used as modulators.

Thyratrons produce RF interference in two ways. First, high-frequency components of current are generated during their switching action. Second, the arc discharge inside the thyratron tube is a source of both conducted and radiated radio-frequency interference.

RF interference from thyratrons may be reduced or eliminated by proper shielding, and bonding, and by installing filters in the power supply and output leads. When the interference is not too severe, shielding of the tube to prevent direct radiation, bonding of the shield and the base to a large metallic structure, and installation of feedthrough or bypass capacitors usually suffice. When large amounts of power are involved (as in radar modulators), more elaborate shielding involving the entire unit and extensive use of feed-through capacitors or filters are required. Resistors are effective as long as they do not disrupt normal circuit operation.

WIRING

Interference is generated in signal circuits by primary wiring systems or by improper wiring of high-level driving devices to low-level signal-handling devices. Wiring interference is produced by resistive or inductive voltages, electrostatically induced voltages, or electromagnetically induced voltages from power and control lines.

Inductance and series resistance in the power lines of signal-handling devices results in resistive and inductive voltages. In the correction of such interference voltage, circuits that share common wiring must be found.

Voltages are induced electrostatically by the distributed capacity between closely situated DC circuits of various levels. If one is a low level circuit, any induced voltage may cause serious troubles. Leakage current through coupling capacitors in AC circuits develops voltages across inductances in the series path (Fig. 5-4). Interference signals at the input to the amplifier result from the drop produced by current I_c through R_1 and R_2.

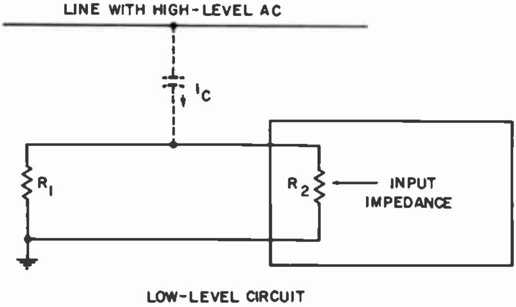


Fig. 5-4. Capacitance between high- and low-level circuits.

Current-loop fields of power lines (and other power wiring) produce electromagnetically induced voltages. It is therefore advisable to employ whatever means available in arranging power circuits to minimize such loops; e.g., twisting of leads. Fig. 5-5 shows that the amount of flux cutting the twisted lead is a good deal less than that cutting the open circuit. If twisting is not sufficient, however, either magnetic current shields, flux shields, or both, must be employed. No matter what is done, however, some ambient magnetic fields are always present, and it is necessary to protect the highly sensitive circuits from them.

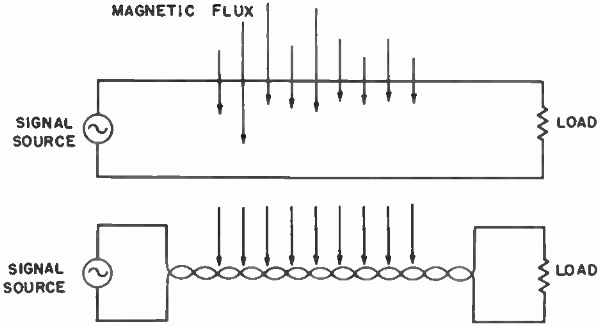


Fig. 5-5. Reducing the flux cutting a circuit by twisting the leads.

GROUND INTERFERENCE

Ground interference is usually a combination of electromagnetically induced voltages and resistive and inductive voltages in common wires. A typical ground system, with a loop *CDGH*, is shown in Fig. 5-6. In the presence of a varying magnetic field, a voltage will be induced in the loop, which must be broken so that no current flow is possible.

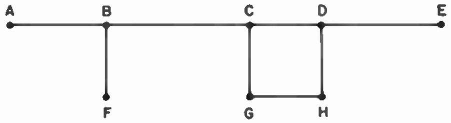


Fig. 5-6. Ground circuit with loop.

A grounding system with no loops, but with a number of common wires, is shown in Fig. 5-7. Economic considerations usually make this type of wiring desirable, even though the inductive voltages in such a situation may prove to be harmful. Bypass capacitors across the output of each circuit supplying current to the ground system will aid in reducing such inductive voltages.

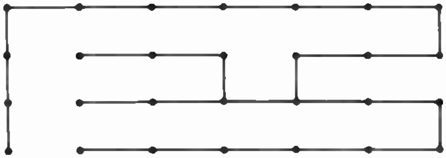


Fig. 5-7. Ground circuit with common leads.

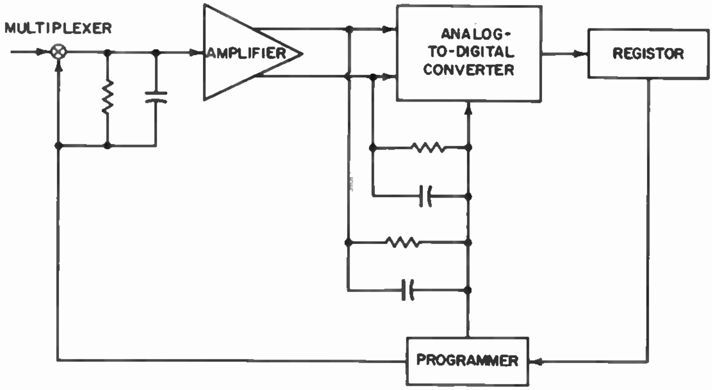


Fig. 5-8. System with leakage between digital and analog circuits.

INTERFERENCE BETWEEN HIGH- AND LOW-LEVEL DEVICES

It is often necessary to use a high-level device, such as a multivibrator, to provide the triggering signal, or drive, to a low-level device such as a multiplexer. In such cases it is important that the signal does not introduce error into the operation of the low-level device. Such an operation is shown in Fig. 5-8. Possible leakage paths (indicated by the shunting resistors and capacitors) can be minimized by providing ground returns for signals, and by using shielded isolating transformers in the signal circuits, as shown in Fig. 5-9.

TRANSDUCERS

Input transducers may operate under extremely bad electrical or electromagnetic conditions, such as being randomly and unavoidably grounded at widely separated points. A typ-

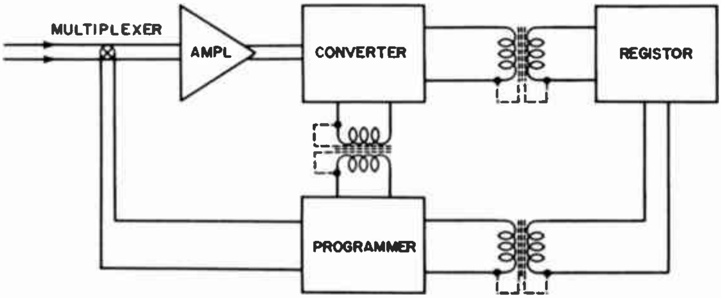


Fig. 5-9. Corrective measures to improve circuit of Fig. 5-8.

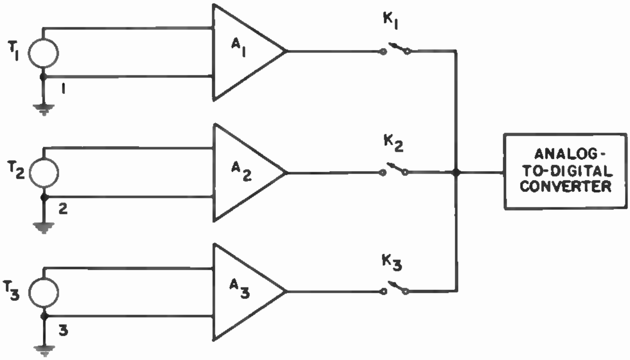


Fig. 5-10. System with multiple inputs from transducers.

ical multi-input system is illustrated in Fig. 5-10. Fig. 5-11 shows one of the transducers (T) of Fig. 5-10 and how noise originates in it. One source is the common-mode voltage ($e_{c\text{-}m}$) generated in the transducer ground (common-mode voltages are generally the result of impedances in AC-equipment grounds); another is the voltage electromagnetically induced across e_x. The third type is due to the voltage generated by capacitive currents flowing through imperfect shields.

Coupling of interference also occurs between channels. In the circuit of Fig. 5-12, with channel 1 connected and channel 2 open, capacitive coupling appears across the contacts of K_2. The amount of coupled interference e_c depends on resistance R_g between the system ground and earth ground.

Two methods of minimizing the effects of the interference paths in these circuits are shown in Fig. 5-13. Relay K switches the capacitor from source to system for isolation (Fig. 5-13A).

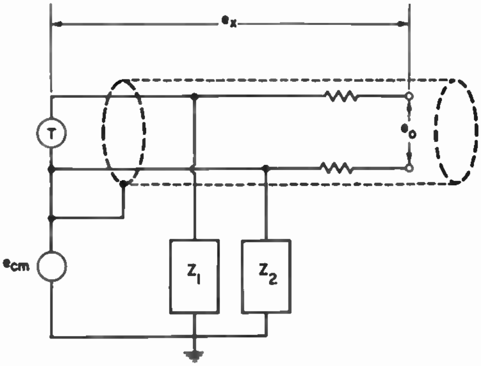


Fig. 5-11. Sources of interference in a transducer.

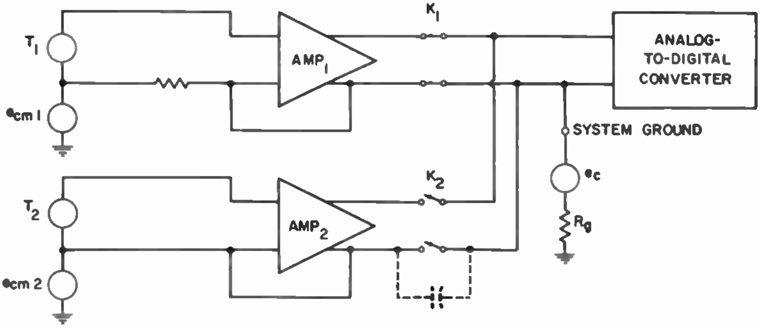
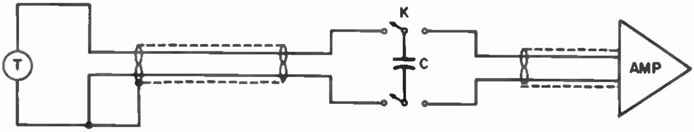


Fig. 5-12. Coupling interference between two transducer circuits.

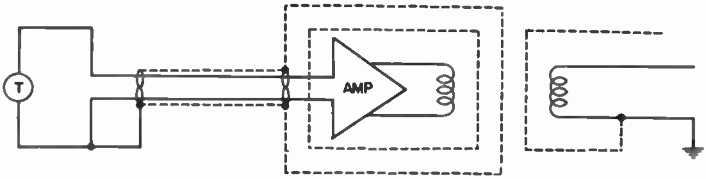
Sometimes the distributed capacity across the relay necessitates shields extended into the relay. Fig. 5-13B shows triple shields, required where the sampling rate prevents switching of the input capacitor.

ANALOG AMPLIFIERS

Analog amplifiers (Fig. 5-14), often used to drive analog-to-digital converters and enternal recorders, transponders, etc., must be wired into the equipment quite carefully to lessen interference problems. A system wired to reduce pickup of electric and magnetic fields is shown in Fig. 5-15. A shielded isolation transformer is desirable between amplifier and load (Fig. 5-16) when an analog circuit drives a grounded load circuit. If the output is DC, a DC converter should be used to provide interference-free coupling to the load (Fig. 5-17).



(A) Capacitive.



(B) Triple shielding.

Fig. 5-13. Two methods of reducing transducer interference.

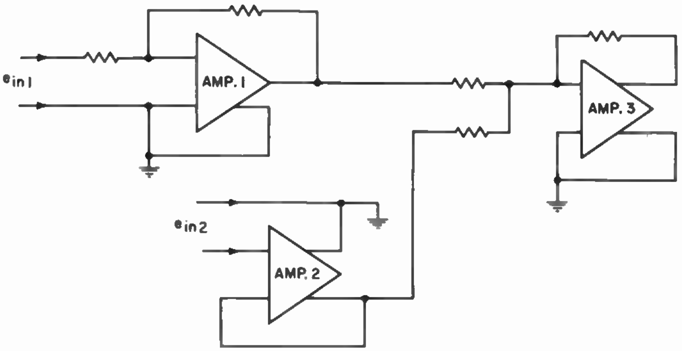


Fig. 5-14. Typical analog-amplifier system.

AC POWER DISTRIBUTION

Voltage transients, resulting from a varying load, occur in all public (also commercial and industrial) power systems. Often followed by damped oscillations, these surges are superimposed on the line voltage and are known as conducted power-line interference. They may be high in magnitude with respect

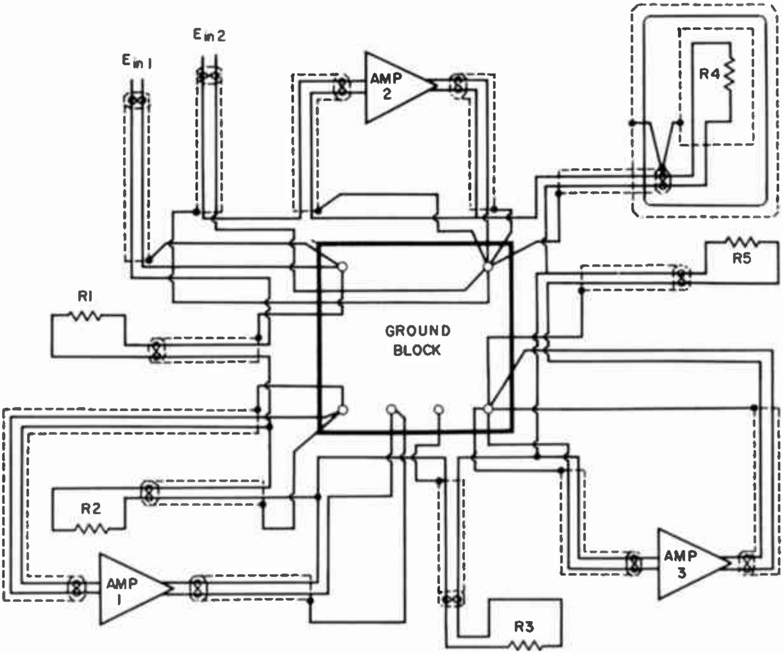


Fig. 5-15. Wiring to reduce interference of circuit shown in Fig. 5-14.

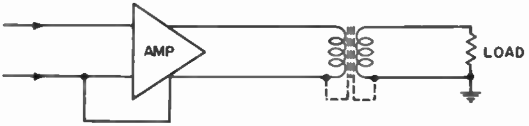


Fig. 5-16. Amplifier connected to load through isolation transformer.

to the normal system voltage and may appear from line to ground or line to line. While their frequency is much too low to be termed RF interference, it can be very harmful in many instances and therefore deserves treatment here.

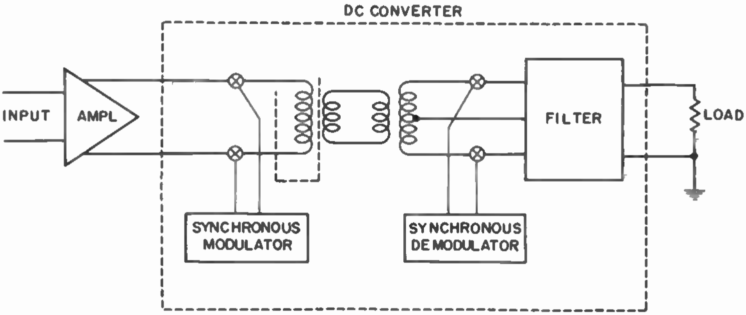


Fig. 5-17. Amplifier connected to load through DC converter.

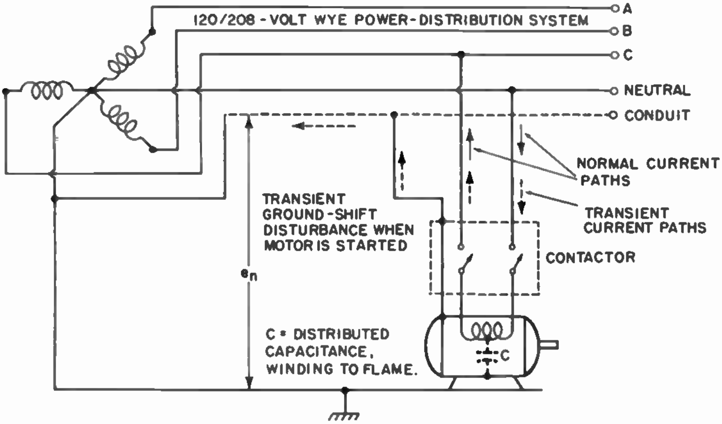


Fig. 5-18. Distribution circuit supplying power to a motor during switching phase.

Power-frequency current flows in definite paths under steady-state conditions. While a switching surge occurs, and momentarily thereafter, however, the high frequency effects of the system are of some concern. Current flow in conduit, for example, is small at the fundamental frequency, with little voltage drop produced; during switching, the conditions become altered.

Starting the motor shown in Fig. 5-18 causes a high inrush current of fast rise time. A good portion of this transient current flows in the ground leads and conduit to neutral, due to the capacity between the wiring and frame. The voltage drops in the conduit are determined by the degree and rate of the current change, and the resistance and inductance of the conduit. Disturbances of this type prevent proper operation of control systems deriving power from the affected distribution network.

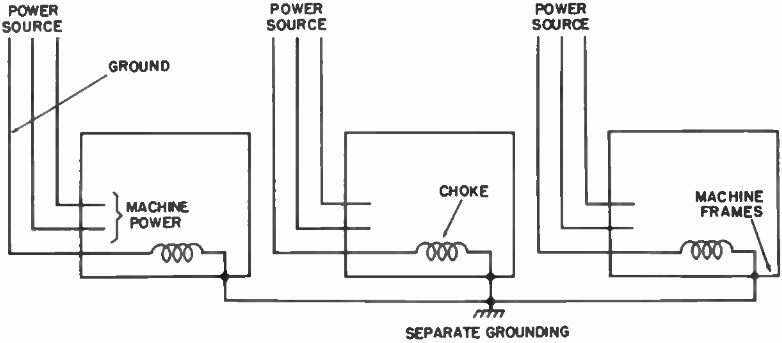


Fig. 5-19. Grounding circuit for systems receiving power from several sources.

The magnetic fields produced by the transients in the metal frames of the system determine whether or not a malfunction will occur. Transient potential differences develop where one portion of the system draws power from another supply. These disturbances often cause improper operation.

Systems consisting of several pieces of equipment which are subject to malfunction due to ground-shift disturbances should obtain power from separate services (Fig. 5-19). The wiring should be through conduit, and a grounding wire should be connected to the same earth connection point as the power service. A choke which will isolate the high-frequency ground-shift disturbances, but which will offer a low impedance to 60-cycle fault current, should be used in the connection to the frame. The choke must have a low distributed capacitance to be effective at high frequencies. A high-permeability ferrite toroid consisting of just a few turns will develop the inductance at low capacitance.

Motors that are turned on and off while sensitive units of the system are in operation, require special precautions in wiring. Twisted pairs of Type SJ cable encased in conduit should be used for all wiring. Filters should be provided in the motor branch of the power supply (Fig. 5-20), and also in the supply for the electronic circuits. A metal box should be employed to entirely enclose the contactor, and the control circuit should be decoupled with feedthrough capacitors. Diodes with a sharp break in the current-versus-voltage characteristic should be used for surge suppression.

Reduction of conducted power-line interference with filters will not allow poor practice in AC wiring. An example is a single line not referenced to a return line which can act as an antenna loop and be sensitive to radiated magnetic fields. Such a field will cause current flow in the single AC line and produce an interference source which will affect circuits sensitive to reradiation.

AC POWER FILTERS

The filters used as suppression devices in AC power lines are low-pass networks designed to pass the 60-cps power with negligible loss. They are generally designed to attenuate undesired frequencies starting at 150 kc, up to 100 mc. Filters to attenuate frequencies from 100 mc down to 1 kc (or even lower) are generally too bulky and expensive, requiring large shunt capacitors and iron-core series inductors. To obtain the most effective filtering over a wide band, more than one stage of filtering is required, with some overlapping. Most systems are capable of operating satisfactorily with an environment of 150 kc or lower conducted power-line interference.

Sensitive circuits may malfunction due to the presence of low-frequency interference. If these circuits are used, it is better to shield the AC wiring with a ferromagnetic material rather than attempting to filter the power supply.

For all such filters, the line-to-ground capacitance is the same, and so is the total series inductance. The actual value of capacitance used is determined by safety requirements, and the actual value of series inductance by the allowable line-to-line voltage drop. The latter should not, as a rule, exceed 1%

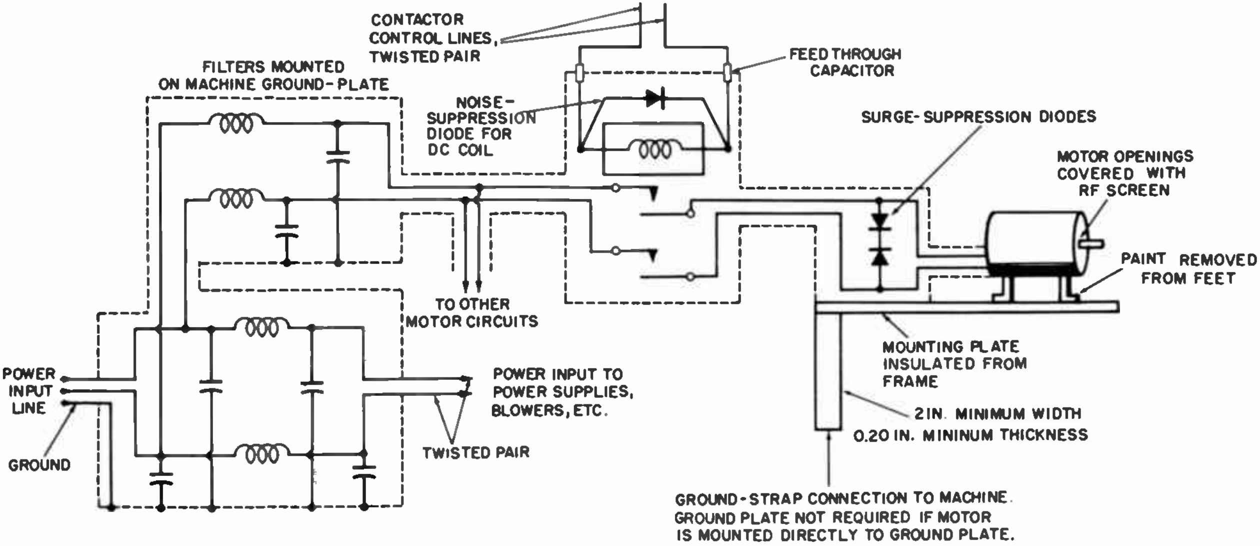


Fig. 5-20. Interference-suppression circuit for motor power supply.

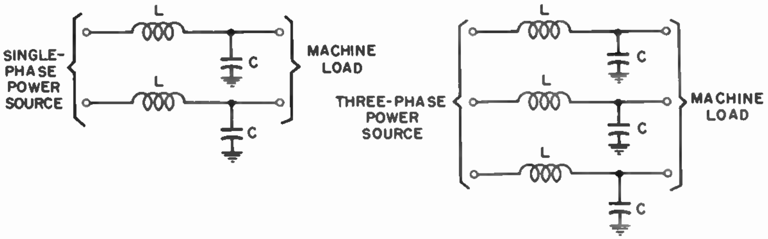
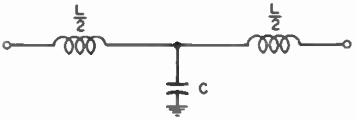


Fig. 5-21. L filter, used when interference is present in power source.

of the line-to-line voltage. When filters are connected in series with lines supplying large motors, the inrush current will be high and the series inductance must be able to withstand the severe environment.

The L-type filter shown in Fig. 5-21 is used to attenuate interference entering equipment from a power system. If the requirement is for a filter to attenuate conducted power-line interference leaving equipment and entering the power system, then the L filter may be used, with the line and load connections reversed. To attenuate in either direction, the T-filter shown in Fig. 5-22 may be used. Its attenuation is higher than

Fig. 5-22. T-filter, used to attenuate interference in both directions.

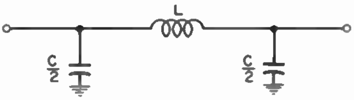


that of the L-filter. A filter with still higher attenuation is the pi-type shown in Fig. 5-23. For this reason it is the type most commonly employed.

Typical insertion-loss curves for pi- and L-filters which use feedthrough capacitors are shown in Fig. 5-24. Such capacitors allow good high-frequency attenuation; lead types resonate and result in poor attenuation at high frequencies.

The voltage that will be applied to the filter capacitors must be considered (Fig. 5-25) and allowances made for voltages higher than those normally encountered. While the power-distribution system is lightly loaded, the voltages can be 10% higher than normal. All capacitors in a given filter must have the same voltage rating—even though the actual voltage may be zero in some cases because, at the time of installation, the

Fig. 5-23. High-attenuation pi-filter.



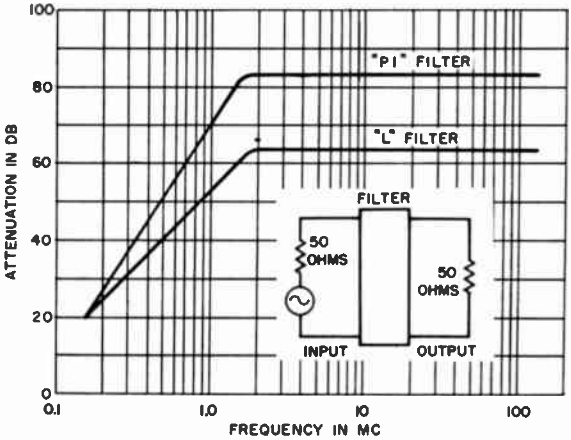


Fig. 5-24. Typical insertion-loss curves for pi- and L-filters.

grounded conductor line was connected to any one of the input terminals. Capacitors used in filters should be rated for a continuous service life of five years.

A bleeder resistor must be connected from the line to ground; it should be included as part of the filter assembly. Its value

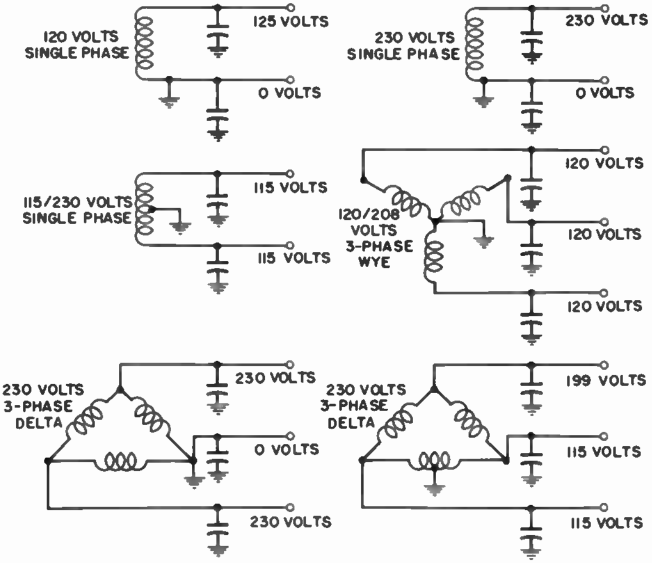


Fig. 5-25. Voltages applied to filter capacitors for various types of supplies.

must be such that the voltage will decay to less than 60 volts in five seconds. The maximum peak voltage, multiplied by 1.41, may be used to determine its value.

The maximum allowable value of total capacitance in a filter should be such that the current flowing in the ground wire does not exceed 5 ma. This is a safety requirement which considers the possibility of a ground wire becoming disconnected. Should this happen and someone standing on the ground touches the metal frame of the equipment, the maximum possible current flow through the body would be only 5 ma (actually it would be limited to a value somewhat less than 5 ma because of the body resistance).

SIGNAL-CIRCUIT WIRING

Equipment not electrically shielded is exposed to undesired radiated magnetic fields. The switching of a motor or other high-inrush current device near a sensitive system can cause a radiated magnetic field of such intensity that the equipment will malfunction unless proper precautions are taken. Currents may be induced in the metal cases of equipment by magnetic fields; this current can induce other fields in sensitive circuits, or near them.

It is the general practice to reduce problem interference to acceptable levels at the source. This is not always possible, however, nor is it always practical to enclose the equipment in a shielded area. The best solution is to use low-inductance wiring techniques so as to reduce the sensitivity of the equipment to magnetic fields.

Signals should not be transmitted over a single wire with the DC ground used as a return path; circuit inductance is high because of the large loop formed. This loop is extremely sensitive to magnetic fields, which can cause current to flow in the loop circuit. The resultant induced voltage can then produce a malfunction in the system. The common DC return has another disadvantage—a step change in current, caused by one of the signal circuits, will modulate the other circuits to a degree determined by the magnitude and rise time of the signal current and the return-line impedance. This can cause a malfunction in the circuit where the modulation is induced. When low-inductance wiring is used for signal circuits, the current will flow in well-defined paths and keep the interference induced in other circuits to a minimum. Therefore, it is advisable to use twisted pairs or coaxial cables for all signal circuits.

DC POWER DISTRIBUTION

Twisted pairs or pairs of plates located close together should be employed for all DC distribution lines. The maximum allowable resistance of such lines is determined by the peak current and the maximum allowable voltage drop in the lines. Whenever the conductor is so large that it is difficult to use, then more than one twisted pair should be connected in parallel. If DC distribution must be provided over a considerable distance, a bus like the one in Fig. 5-26 should be used; its low resistance and inductance offers good dynamic and steady-state characteristics.

Decoupling

Where a circuit requires a transient, high-amplitude, fast rise-time current, it is usually necessary to decouple the circuit from the DC supply. In this way the dynamic voltage drop is limited and the interference voltage on the supply line kept within limits. Only the resistance and inductance of the DC distribution wiring from the bus terminals to the point of decoupling need be considered in the design. In the decoupling circuit of Fig. 5-27, these impedances are indicated as *L* and *R*. The decoupling capacitance required to limit the interference voltage to a specified value is indicated as *C*, while Z_S is the maximum allowable impedance at the decoupling point.

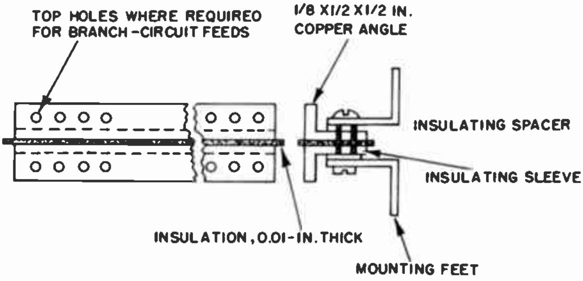


Fig. 5-26. Design for a DC distribution bus.

When a large value of decoupling capacitance is required and more than one capacitor is used for effective results over a wide band of frequencies, three different types of capacitors should be employed, such as a paper, a mica or ceramic, and an electrolytic.

To reduce the decoupling required, the series inductance must be reduced and/or the series resistance increased. It is difficult and expensive to reduce the wiring inductance, which is contained within the lead wires and socket terminals; it is simple to add a series resistance. If the total value of series resistance is made equal to the maximum allowable impedance of the circuit at the decoupling point, the voltage will remain within the required limits—both while the current is transient, and while it has a steady-state maximum value.

Making the series resistance equal to the maximum allowable circuit impedance at the decoupling point is possible only if the decay time of the current is equal to or longer than the rise time. When the circuit requires a steady-state plus a transient current, the amount of decoupling capacitance may be reduced if desired. In such a case, the series resistance is not made equal to the maximum allowable circuit impedance at the decoupling point, and a correction factor is required. The maximum allowable circuit impedance at the decoupling point, Z_S, is now equal to the DC voltage (per cent of interference tolerance) divided by the peak current (steady-state current) times 100. The value of series resistance R is now equal to the DC voltage (per cent of drop) divided by the peak current times 100.

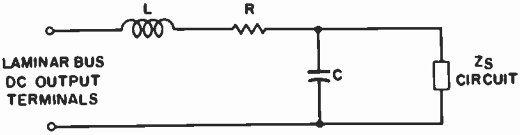


Fig. 5-27. Decoupling circuit for DC supply.

When these values of Z_s and *R* are determined, their ratio can be obtained and the curve of Fig. 5-28 employed to arrive at a correction factor for the decoupling capacitance. The value of capacitance obtained from Fig. 5-28 is divided by the correction factor from Fig. 5-29 to obtain the reduced decoupling capacitance.

Other Considerations

Several other considerations of a system are important in interference reduction. The metallic framing should be free of paint and be protected against corrosion by plating, which will assure low contact resistance. Subassemblies should be securely fastened to the structural members to assure low contact resistance. Any shock-insulating devices should be electrically bonded to the frame, using the shortest possible length of wide, flexible conductor.

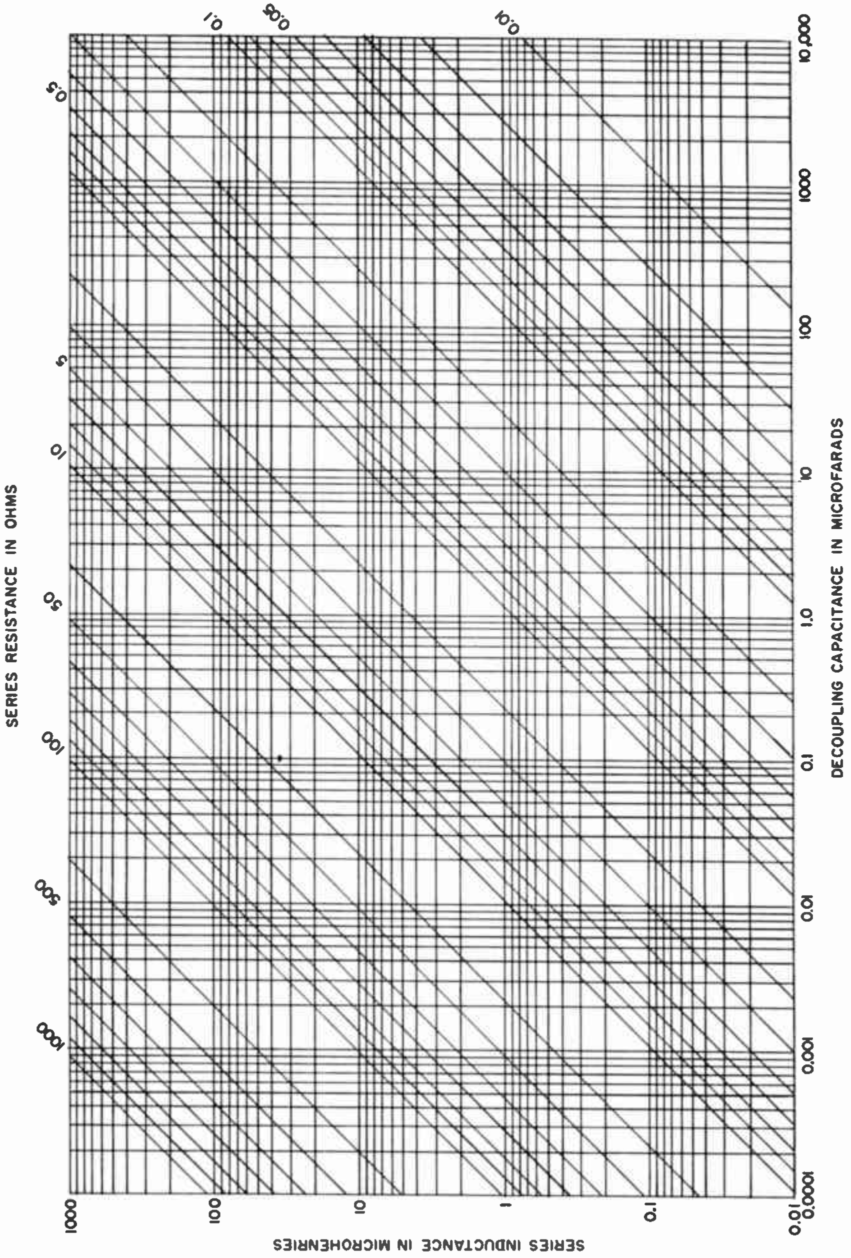


Fig. 5-28. Chart for determining decoupling capacitance when series inductance and resistances are known.

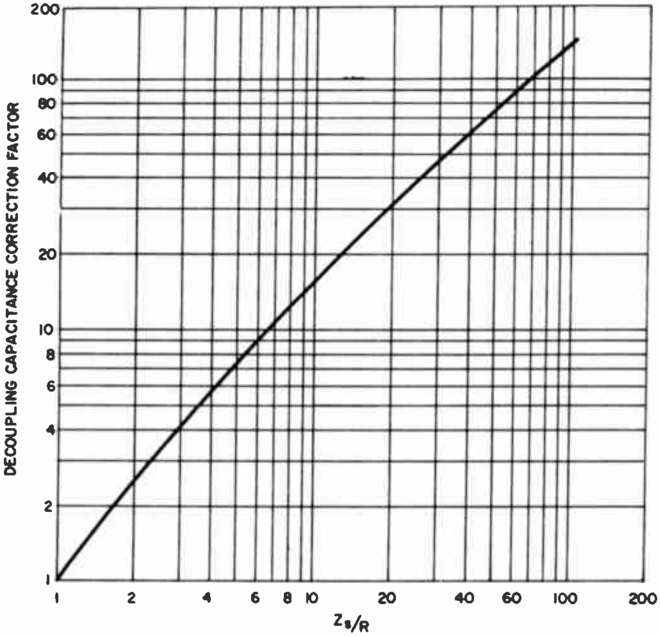


Fig. 5-29. Correction curve for determining decoupling capacitance when there is a steady-state DC capacitance.

Each equipment which may be used with other equipment to form a complete installation should be provided with a copper ground-reference bus. It should be located at the bottom of the equipment cabinet, run the entire length, and securely bonded or bolted at the intersections of the frames.

Special consideration must be given to circuits which operate from low-level inputs (such as photo-cell circuits, where the input may be as low as 1 microvolt). Such circuits should be enclosed in a water tight compartment to which a single-point ground connection is made to the equipment ground bus. All power supplies entering the compartment should be bypassed with feedthrough capacitors located as near the compartment grounding point as possible.

FLUORESCENT AND CARBON-ARC LAMPS

A fluorescent lamp contains low-pressure mercury vapor which is ionized by the flow of electrons in the tube. The subsequent deionization causes ultraviolet radiation. This radiation then excites the phosphor coating on the inside of the tube,

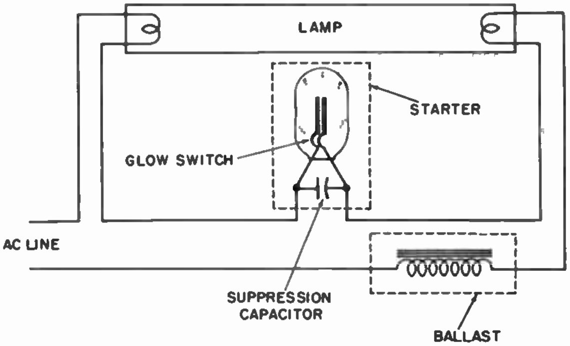


Fig. 5-30. Installation of fluorescent lamp with starter.

causing it to glow. Since this process essentially employs a continuous arc, it is a generator of RF interference.

The interference can be transmitted to receivers by being radiated directly from the lamp or from the power leads; or it can be transmitted, by conduction, through a common power-supply system. Suppression of direct lamp radiation is impractical because the frequencies involved are so high that adequate shielding would seriously interfere with the normal lighting function of the lamp.

Most of the interference conducted or radiated by the power line can be eliminated with the aid of a feedthrough or bypass capacitor. For systems that employ starters, this capacitor may be placed across the starter terminals, as indicated in Fig. 5-30. For starterless systems, the capacitor is mounted in the ballast (a current-limiting device which prevents the tube from being overloaded), as illustrated in Fig. 5-31. In

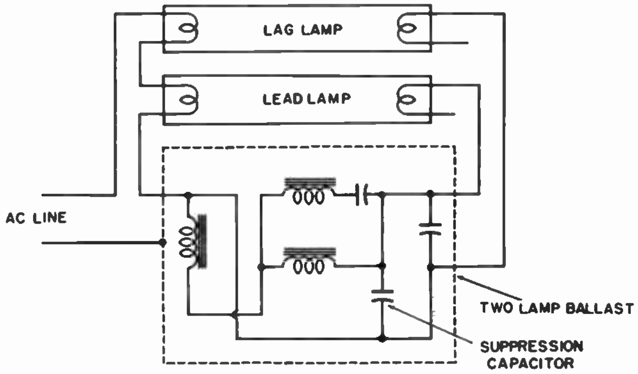


Fig. 5-31. Starterless fluorescent lamp.

most lighting fixtures these capacitors are built in, except quite often where manual starting is employed. A capacitor with a value ranging from 0.006 to 0.01 mfd should then be installed across the lamp leads; where it is desirable to further reduce the interference in power leads, filters are required.

Generally, the use of fluorescent lighting near electronic equipment or sensitive wiring is not recommended, since incandescent lighting is a good and readily available non-interference-producing substitute.

Carbon-arc lamps are widely used in projectors and for reproduction work; they employ a continuous electric arc between two carbon electrodes and are therefore severe interference generators. Because carbon-arc lamps are usually employed in small enclosures and their light is focused in a particular direction, partial shielding is feasible and effective. In addition, feedthrough or bypass capacitors must be installed in or at the power leads, as described for fluorescent lamps.

GAUGES AND INSTRUMENTS

Only the most widely used gauges and instruments will be treated here. Other types, which may be encountered only occasionally, vary considerably in their principles of operation and must be treated individually.

Automotive-type gauges may be classified as Bourdon and electrical. The Bourdon type operates independently from the electrical system and for this reason may be completely disregarded as a source of interference. The electrical type consists of a sending and an indicating unit, which must be considered separately in a discussion of interference suppression techniques.

The Sending Unit

Sending units are generally variable resistance and thermal. Variable-resistance types are simply elements whose resistances vary with temperature, pressure, or the level of a fluid. Unless defective, they are not in themselves a source of interference and should be used whenever practicable. Most thermal types utilize one or more bimetallic strips and breaking contacts. The contacts open and close automatically and generate high-intensity interference impulses, which are radiated by the connecting wiring. Since these pulses are of relatively short duration, this interference extends over a wide frequency range. Often their make-and-break action is a greater source of interference than are many major electrical units. The use of such thermal-type sending units should obviously be avoided.

Indicating Units

Indicators are of two major types, magnetic and thermal. There are several kinds of magnetic types, but all are merely forms of ammeters. Since there is no interruption of current, in this no interference is generated.

There are also two types of thermal indicators. One uses a bimetallic strip connected to the pointer and surrounded by a small heating coil. The current through the coil heats the strip, deflecting the pointer. This type of indicating unit is not a source of interference. However, it is frequently used in conjunction with the thermal-contact sending unit, a serious source of interference.

The other type of thermal indicator is basically similar to the first except that an additional bimetallic strip is used to open a set of contact points when the coil becomes overheated. The opening and closing of these contacts produce an erratic, pulse-type interference. Sometimes the contacts remain partially open, resulting in continuous arcing, and hence a steady interference which increases and decreases randomly in intensity. This source of interference can usually be identified readily by jarring the indicator; this will momentarily start or stop the interference.

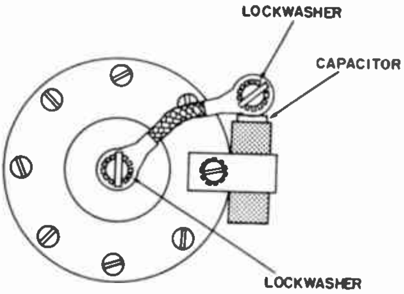
Suppression Measures

Whenever a choice exists, the gauges and instruments should be the inherently interference-free variable-resistance and the magnetic types. Gauges and instruments for all common applications are available in these types.

The thermal-interrupter type sending unit is suppressed by means of a 1- to 2-mfd feedthrough capacitor. In some cases a metal tube, extending from the body of the sending unit to the capacitor case, must be added in order to ground the capacitor and shield the sending-unit terminal. Although such an installation is effective, its cost approaches and may even exceed that of a sending unit which does not produce interference. Furthermore, the life of its contacts may be somewhat shortened by the addition of the amount of capacitance necessary for adequate suppression of the interference.

Interference from the thermal-type indicator with contact points is reduced by connecting a resistor, of the lowest resistance value which will not affect the indication, directly across the contacts.

Fig. 5-32. Bypass capacitor at indicating unit.



Here is a good rule of thumb for gauges and instruments: if either the sending or indicating unit employs contacts (or a commutator) which make and break an electrical circuit, RF interference will be generated and suppression treatment will be required. Adequate suppression of such sources is obtained in most cases by one of two methods:

1. Application of a feedthrough or bypass capacitor directly to each terminal of the unit containing the contacts, or,
2. Shielding of the leads between the sending and indicating units with a suitable feedthrough or bypass capacitor applied at the positive terminal of the indicating unit.

Considerable care must be taken in the second method to prevent the interference from coupling into other instruments

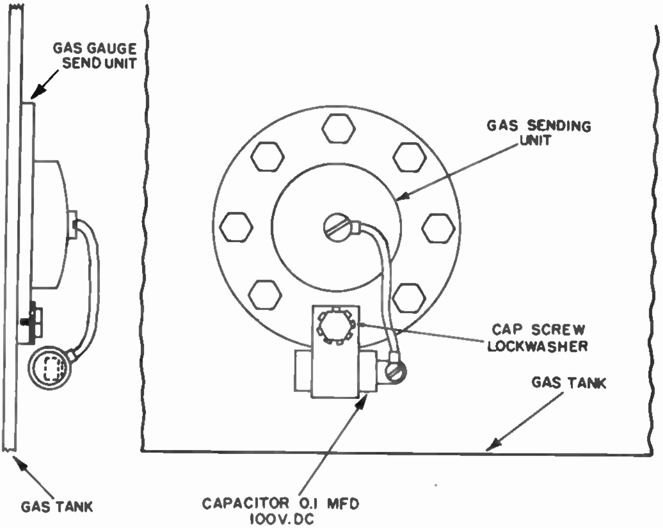


Fig. 5-33. Gas-gauge sending unit.

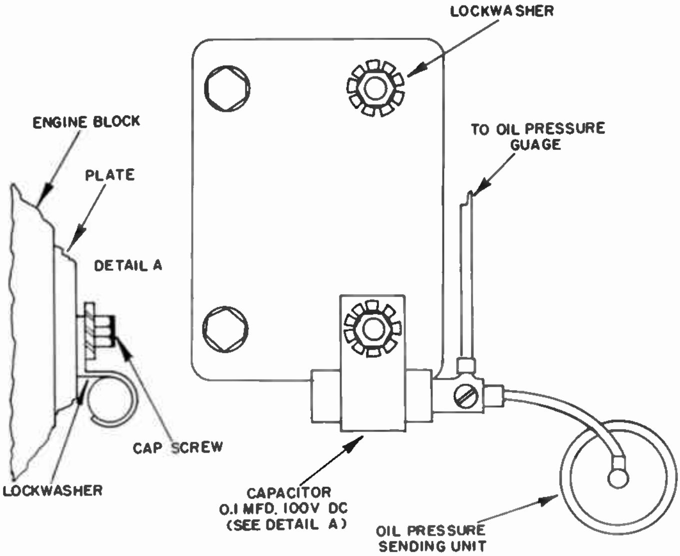


Fig. 5-34. Oil-pressure sending unit.

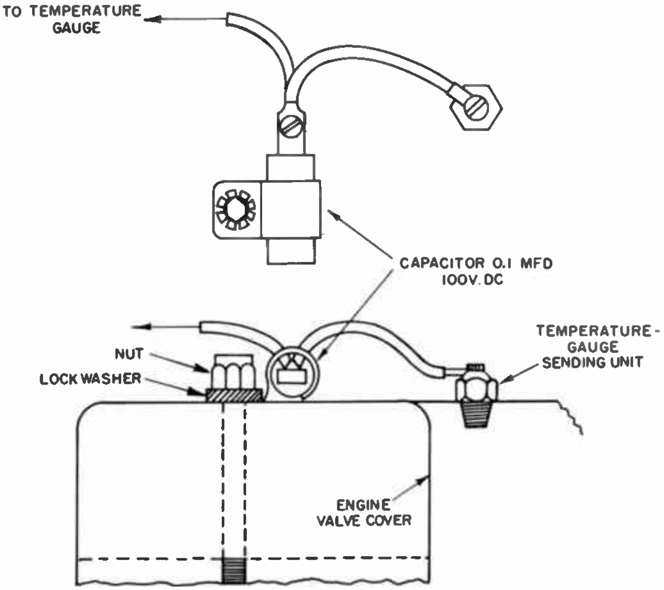


Fig. 5-35. Temperature-sensing unit.

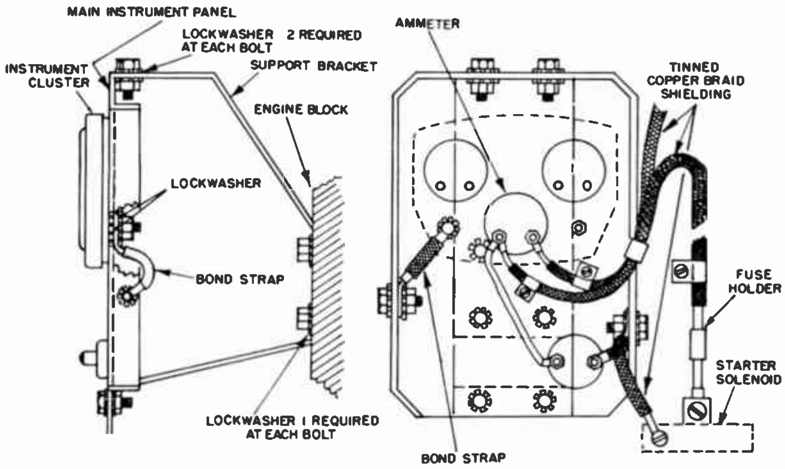


Fig. 5-36. Diesel-engine instrument panel.

or wiring. A poorly grounded instrument panel, when used to terminate shielding or to serve as a ground for bypass capacitors, will couple the interference more effectively than the original offending circuit. Proper bonding of the instrument panel is of utmost importance here.

The suppression measures described herein are illustrated in Figs. 5-32 through 5-36. Fig. 5-32 shows the bypass capacitor at an indicating unit; and Figs. 5-33, 5-34, and 5-35 the suppression of sending units. Proper bonding of an instrument is indicated in Fig. 5-36, which illustrates the shielding of the leads to an ammeter. When the ammeter is connected directly to the DC system, as for example in a Diesel engine, its leads may carry interference from a variety of sources and consequently require shielding.

CHAPTER 6

Semiconductor-Circuit Interference

Many electronic devices utilize transistors as switching devices and diodes as rectifiers; such circuits often produce high levels of RF interference. That produced by the transistor is a square wave, while the diode produces RF interference of a sinusoidal characteristic. In addition, transistor circuits are vulnerable to susceptibility requirements, since they do not have the isolation of the filament and/or a filament cathode associated with the typical vacuum tube. Instead they have a DC voltage applied directly to one of the transistor elements; this brings about the necessity of ripple-free (AF or RF) DC power supplies.

High-speed solid-state circuits place severe restrictions on the power-distribution and communications-lines design of a system. Circuit parameters which are of little importance in the design of vacuum-tube equipment become of major importance in solid-state circuits. Transistors require relatively high currents and low voltages in comparison with those of vacuum tubes. Assuming the DC input power required to perform a certain function is the same for either a vacuum tube or transistor circuit, a comparison can be made of the DC input power distribution-line parameters for both circuits. If the DC operating voltage for the solid-stage circuit is one-twentieth that of the vacuum-tube circuit, all circuit parameters for the solid-state circuit, including the DC distribution lines, must then be adjusted by a factor of 20^2, or 400. There is an accompanying automatic reduction in impedance in the solid-state device; its wiring resistance and inductance should be reduced by 1/400 and the capacitance increased 400 times.

The reduction in resistance can easily be accomplished by increasing the cross-sectional area of the conductors; increasing the area 400 times will result in only a small decrease in resistance, however. An increase in the capacitance cannot be obtained with conventional wiring geometry; special techniques are required.

A large copper plate such as that shown in Fig. 6-1 is usually considered to be a low-impedance conductor. In a vacuum-tube circuit, such a plate is a satisfactory conductor, since the voltage drop for current pulses with fast rise times is small in terms of the vacuum-tube impedances and voltage levels. This is not true for the low-voltage, low-impedance solid-state circuits, however: a current pulse produces a voltage drop across the tube plate, and this drop is relatively large compared with the low voltages used in transistor circuits. Also, there is the possibility of interference generation, which can adversely affect circuit operation.

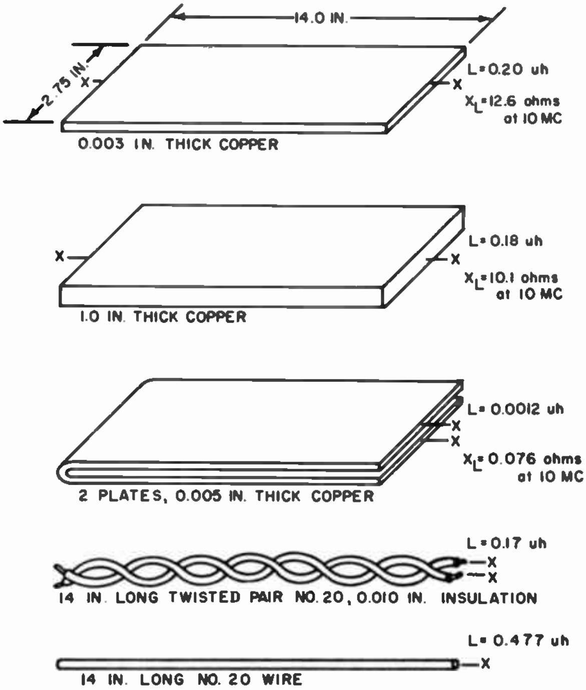


Fig. 6-1. Various conductor configurations.

Increasing the thickness of the plate is effective in reducing the resistance, but has negligible effect on the inductance. As a matter of fact, the twisted pair of No. 20 insulated wires, the same length as the plate, has a lower inductance than the single plate, while the single wire has almost twice the inductance.

To obtain low inductance values, conductors must be placed close together to reduce the magnetic field. A pulse of current flowing in one side of a circuit causes a magnetic field to surround the conductor. The pulse current, as it returns from a lead in the other side of the circuit, causes another magnetic field to surround the conductor; the two are 180° out of phase. If the two conductors are physically close to each other their fields tend to oppose each other and cancel; if not, they become a source of interference. When the conductors are close together, the magnetic field is concentrated between them and they tend to be less of a source of interference.

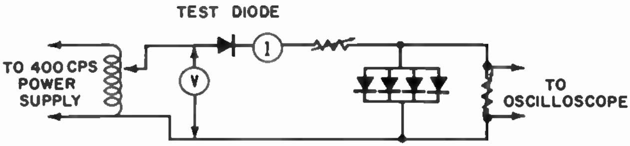
A single wire which is part of a signal-carrying circuit and is subject to the environment of a changing magnetic field will have a voltage induced in it. Whether or not this undesired voltage causes a circuit malfunction depends on the total circuit impedance and sensitivity. The intensity of the magnetic field varies inversely with the square of the distance between conductors. Low-inductance lines (such as twisted pairs) are less susceptible to induced voltages, since both lines are subject to the same field. Therefore, the induced current is small. If perfectly symmetrical twisted pairs and a uniform magnetic field were possible, there would be no induced voltage. Since this is impossible, it is necessary to avoid running low-signal lines near lines carrying high-amplitude, fast-rise-time pulses.

DIODES

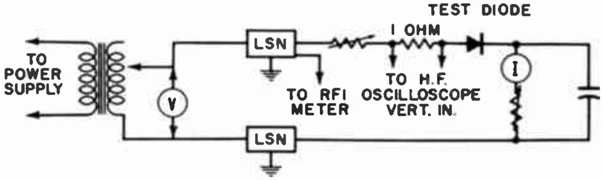
Diodes used in circuits to provide DC power to high-speed switching circuits in computers have several things in common: a fixed forward-to-reverse–current conducting ratio, and a fixed bias or threshold voltage. Also, they conduct during only one half-cycle of the applied AC voltage, and they remain off until an applied voltage overcomes their bias and causes them to conduct.

An understanding of these diode properties, together with an understanding of their RF properties, is important for correct selection of the appropriate diode in correction of a particular interference problem.

The recovery time of a diode can be expressed as the period immediately after a diode has been passing a steady current and is suddenly biased in the reversed direction. This occurs at the time and point the applied AC voltage goes through the zero reference. Fig. 6-2 illustrates two test circuits used for investigating diode-switching transients. The circuit in Fig. 6-2A is used to check the reverse current of a given test diode



(A) Resistive diode-shunted load.



(B) RFI, capacitive load.

Fig. 6-2. Diode switching-transients test circuit.

in a resistive load shunted with four diodes having known fast switching times with respect to the test diode. This set-up can be used to test a large number of diode types; however, the circuit of Fig. 6-2B provides a more realistic circuit in comparison with typical usage, and allows measurement of both RF interference as well as switching transients.

During this switching time, the diode has such a low effective resistance that it allows a heavy reverse current to flow. A typical oscillogram of this action is given in Fig. 6-3. The reverse-current spike is of principal concern in RF-interference control; Fig. 6-3 also illustrates the on and off times.

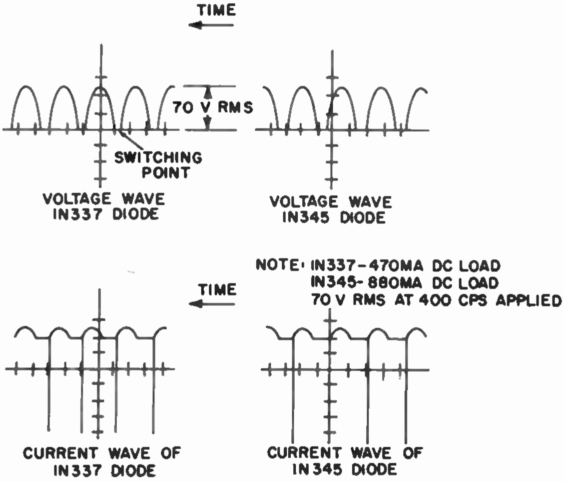
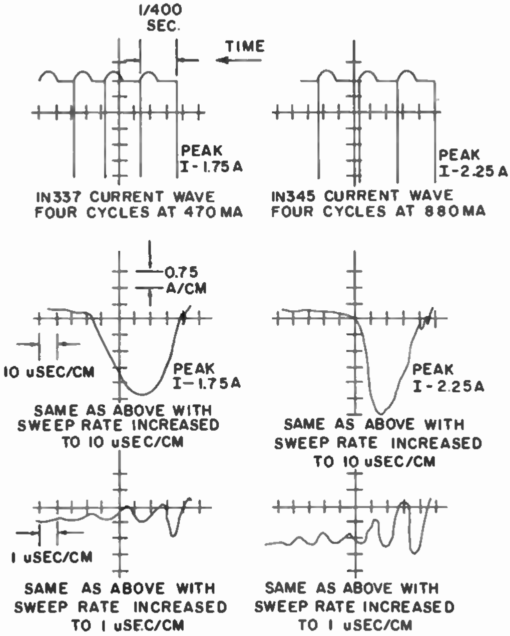


Fig. 6-3. Diode voltage and current waveforms.

In Fig. 6-4 the original oscillogram of Fig. 6-3 is shown, together with a time expansion of the current waveform. This illustration shows clearly that from both an amplitude and a time consideration, the RF-interference voltages are the result of the reverse-voltage spike.

When the current spike is explored, as shown in Fig. 6-5, transient data taken with a 1N337 and 1N345 at several load-current switching densities indicate that the 1N337 is the better choice for minimum transients at loads up to 470 ma. Fig. 6-6 depicts the RF transient comparison of 1N337 and 1N345



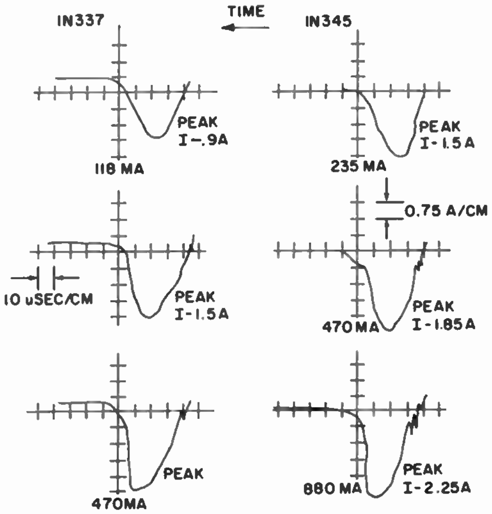
NOTE: IN 337-470 DC LOAD; IN345-880 MA DC LOAD

Fig. 6-4. Oscillograms of diode reverse-current transients.

diodes at a 470-ma load. Again is clearly illustrated the fact that at loads of 470 ma or less, the 1N337 diode produces less RF interference.

With the information thus far as background, it is necessary to keep the current spike in mind, as it will be indirectly referenced in subsequent RF interference tests and suppression techniques.

A typical 1N337 diode, kept at a constant load of 470 ma while the transformer voltage to the test circuit is varied



NOTE: 115 VOLTS AT 400 CPS APPLIED

Fig. 6-5. Oscillograms of diode reverse-current transients at various DC loads.

from 20 volts rms to 70 volts rms and interference measurements are made at 200 kc, shows the results indicated in Fig. 6-7. Also shown is a typical 1N337 with a constant 70 volts

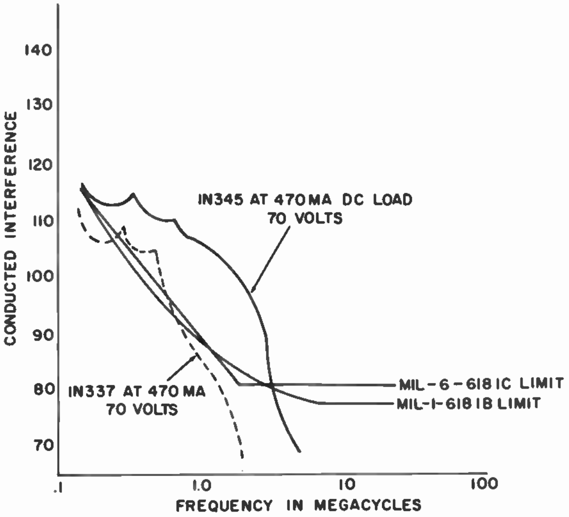


Fig. 6-6. RF interference spectrum of 1N337 and 1N345 diodes.

rms and with the load varied from 100 ma to 500 ma. From the comparison, you can see that it is best to operate a given diode at the lowest possible voltage and load-current density; this means the current spikes should be held to a minimum to keep down RF interference.

Diodes of these types do not follow a typical pattern with regard to the reverse-current spikes. During investigation of the data presented here, the diodes of a given part number that were found to have a minimum current spike were the exception. Diodes of the 1N337 type with the minimum spikes produced RF interference at about one-third to one-half the amplitude shown.

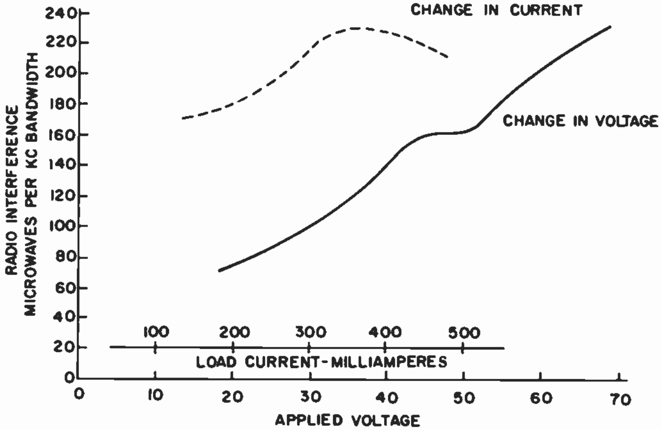


Fig. 6-7. Changes in 200-kc RFI with variation of DC load current and applied voltage.

Under optimum conditions, diodes pass positive halves of a sine wave when used as rectifiers. These sine-wave pulses have a repetition rate of one, two, three, or six times the applied AC voltage, depending on the number of phases and type of rectifier circuit. An infinite number of even harmonics of the repetition frequency are generated from the pulsed sine-wave (half-wave) rectifier. For full-wave rectifiers, these harmonics are composed of both even and odd harmonics. This also applies to the wave produced during the current spikes. RF interference spectroanalysis conducted on vacuum-tube diodes and selenium rectifiers shows that all RF energy is below the background of the RF interference for the vacuum-tube diodes, and usually below required limits for selenium rectifiers. Silicon diodes under the same circuit conditions produce severe RF interference.

The conditions encountered with the half-wave circuits are similar to those for full-wave circuits, except that there is no off time in the output circuit and the transient repetition rate is double. The typical full-wave diode-rectifier circuit uses four diodes, and the RF-interference properties shown earlier for half-wave rectifiers increases in amplitude two to four times, or even more.

Many power circuits use a three-phase full-wave bridge in diode-rectifier circuits. A typical three-phase test circuit is shown in Fig. 6-8. It can be used to measure the current transients and RF-interference properties of the 1N345's at various output-current values. The increase of current spikes from the 100-ma load to the 600-ma load is apparent, as indicated in Fig. 6-9. The peak switching current increases from 0.85 amp at a 100-ma DC load, to a peak of 1.6 amps at a 600-ma DC load. The increase of transients from the 100-ma to the 600-ma load is also readily apparent in Fig. 6-9. The RF-interference properties at 150 kc for these tests are shown in Fig. 6-10.

There is a relatively small change of RF interference between 100 ma and 200 ma, with some increase at 300 ma; however, there is a large increase as the current rises to 400 ma. But as the current is increased still further to 600 ma, a decrease in RF interference can be observed! This is in direct conflict with the previous information on a half-wave or full-wave single-phase bridge circuit.

DIODE INTERFERENCE CONTROL

The first step in the control cycle takes place at the design stage. Here the proper diode must be chosen, keeping in mind the following:

1. The diode selected must operate at the lowest current density in proportion to the manufacturer's maximum rated current.
2. It must have high working and peak inverse voltages.
3. It must use the lowest possible switching rate. This is contrary to normal frequency selection since the maximum switching rate (such as three-phase bridge over single-phase) is used to reduce ripple and the subsequent need for ripple filtering. However, in most applications the audio ripple and RF filter combined will be smaller and lighter than the ripple capacitor (RF filter) for the higher ripple frequency.

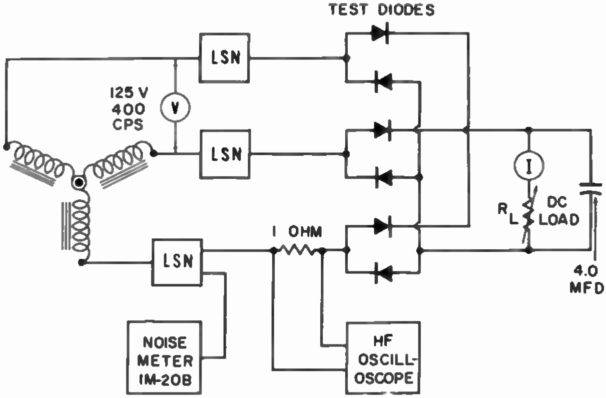


Fig. 6-8. Three-phase test circuit.

4. The diode must have a low recovery time. This is generally a natural by-product with diodes having a larger current rating.

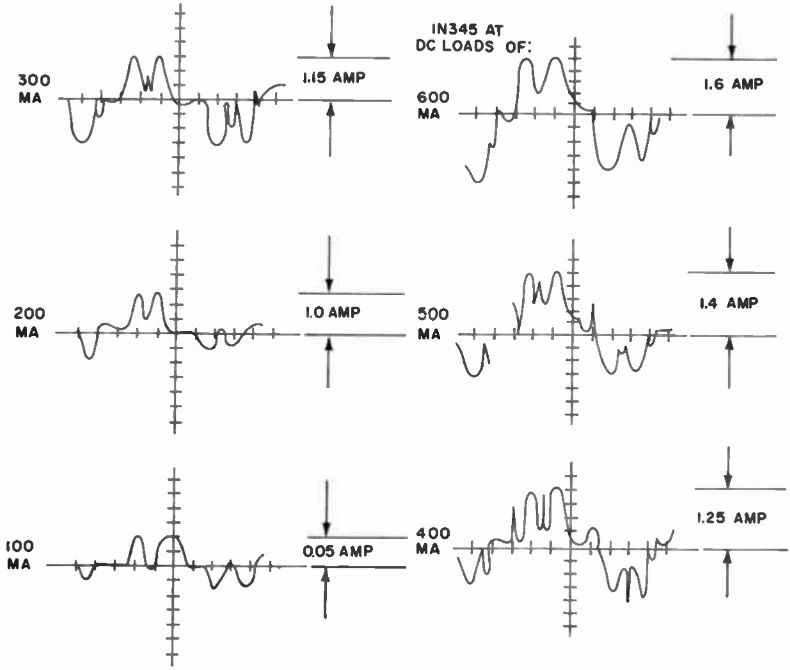


Fig. 6-9. Oscillograms of full line-current cycles (400 cps) in a three-phase full-wave rectifier.

When these conditions have been fulfilled, it is advantageous to test several types of diodes, to determine which generates the least RF interference. Such tests will reduce the cost of equipment considerably by permitting the use of smaller and lighter RF interference filters in the manufactured product. In many cases, network types of RF interference filters will be unnecessary.

The oscillations resulting from the current spikes shown with various diodes have high source impedance properties. This fault can be readily corrected, provided the corrections can be made physically close to the diodes. This point cannot be stressed too strongly. These RF oscillations are very similar to parasitic oscillations (such as in transmitter and receiver circuits) and, as such, must be corrected at the point of origin.

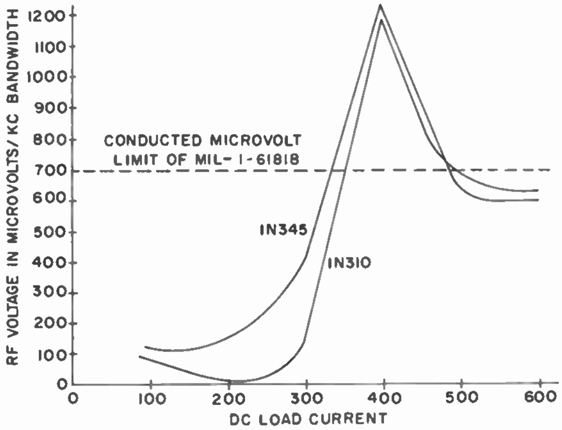


Fig. 6-10. Conducted RFI at 150 kc in a three-phase full-wave rectifier.

Corrective measures may be taken, as shown in Fig. 6-11. All of the circuit or component additions shown reduce the current spike and/or present a low-impedance load to the high-frequency oscillations of the current spikes.

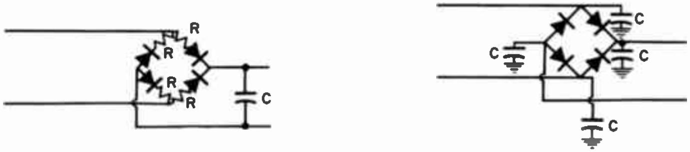
In many cases it is expedient to package the diodes and their correction devices together in one metal container so that the finished diode bank and its filtering device are a separate component. This is especially important where space is a premium. This procedure lends itself best in the case of small-current glass-enclosed diodes, but is not feasible with diodes that require large heat sinks.

The component (diodes and filters) approach prevents the diodes and their associated wiring from radiating or conducting RF voltages to adjacent wiring. In most cases the total volume and weight are less than the parts replaced. There are no set rules in the corrective approaches shown in Fig. 6-11. Figs. 6-11A and C are used for currents under 1 amp. Inductor L in Figs. 6-11A and C is generally 100 to 300 microhenrys for 60-cps operation, and 250 to 750 microhenrys for 400-cps application. As the power-line frequency increases, so does the RF interference, and the circuitry of Fig. 6-11C is generally used. The same circuit is also used where greater attenuation is needed than the inductors alone, offer, as shown in Fig. 6-11A. (The attenuation of voltages in Fig. 6-11A is by transient-current reduction and the resulting reduction of harmonics, rather than by filtering.)

The circuit in Fig. 6-11B, where capacitor C is the only filtering employed is very effective in 60-cps applications. The value of *C* is 0.1 mfd at 60 cps. With proper diode selection, low current density, etc., a capacitor of 0.1 to 110 mfd will correct many 400-cps applications. *C* is in addition to the regular ripple capacitors, which are usually electrolytics and have very little RF attenuation properties. By proper selection, particularly where foil or pellet types of tantalum capacitors can be used, *C* can be both the RF and ripple capacitor.

(A) Low current, low frequency. (B) 60 cycles per second.

(C) Low current, high frequency. (D) High current.



(E) Limiting resistors. (F) Shunt capacitors.

Fig. 6-11. Full-wave bridge-rectifier correction circuits.

When the DC output exceeds the 1-amp current range, power-line filters like the typical one in Fig. 6-11D are used. C1 and *L* form an L-type filter at RF frequencies, while C2 is the high-capacity ripple filter. The inductance offers a double advantage in filtering the RF interference voltages. This inductance limits the inrush current to C2 and the load. Thus, it reduces the total load on the rectifiers, as well as acting as a reactance voltage divider. In many cases the original value of C2 can be lower because of the filtering provided by *L*.

The value of C2 can be reduced by one-half and the remaining value of C2/2 further broken down to two capacitors with values of C2/4, thus allowing the use of tantalum capacitors. The final filter circuit is then a balanced-pi. As previously indicated, this is a typical case where the components used for RF and filtering are smaller and lighter for a given ripple factor and RF-interference specification than if three-phase full-wave bridge circuits were used.

Fig. 6-11E illustrates the use of resistors to limit the switching transients as well as the RF transients. Resistors of 1 to 10 ohms prove very satisfactory where power dissipation in the resistors is not a problem. The diodes manufactured in small glass containers have a sufficiently small current rating to use this correction effectively.

The resistor technique, as well as shunting each diode on both positive and negative sides (Fig. 6-11F), lend themselves to convenient packaging. Capacitor C in Figs. 6-11E and 6-11F range from 0.05 to 0.25 mfd for 400-cps applications. In 60-cps applications, resistors alone have proven effective.

Electrostatically shielded transformers should always be used, to prevent the AC lines from conducting RF energy away from the diodes. The electrostatic shield and the series inductors reduce the RF voltages on the primary lines to the transformer, so that the AC line meets RF-interference suppression requirements without further filtering.

The capacitor and inductor values required for correction or filtering are such that the identical inductor and capacitor can be used for both the audio ripple and RF filter. It is fortunate that virtually all diode RF voltages act like typical harmonics and are reduced in value so that they are seldom measurable above 5 mc. In the lower current range, powdered iron and/or molybdenum-permalloy toroidal inductors with tantalum capacitors provide most efficient filter from the stand-point of size and weight.

In larger current applications, feedthrough capacitors shunted with tantalum capacitors provide an effective filter for both audio and RF frequencies. (By selection of the diodes and filtering techniques shown, diodes rated from the lowest of current levels in the milliampere range, up to 300-amp rectifiers, can provide satisfactory RF-interference suppression.)

Once some experience at correcting diode circuits is gained the appropriate RF interference correction devices will be found to be smaller and lighter than many other types of suppression configurations.

Fig. 6-12 shows preventative circuits for devices where there is continuous need for correction of RF interference. Such devices include the relays and solenoids used on an AC line utilizing diodes, and AC actuators which use diodes to supply DC to operate a brake and/or clutch. Shown is the "before" and "after" of a relay-solenoid circuit and an AC actuator. The "before" conditions produce considerable RF interference; the "after" conditions, by limiting the current spikes, require no correction to meet the same suppression requirement.

In the correction for the typical AC actuator shown in Fig. 6-12C, a tap is brought out (Fig. 6-12D) from the motor winding to the coil diodes.

In the corrective approach for 400-cps relays a resistor is added, as shown in Fig. 6-12B, to limit the inductive-kickback voltage of the relay coil. Otherwise, it will buck the applied line voltage, and both relay coils will be energized at the same time. As a result, the relay will not operate.

For reference purposes, the RF interference voltage of a typical 400-cps aircraft relay is shown in Fig. 6-13. The RF

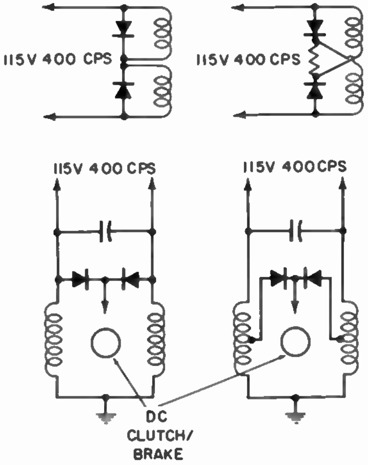


Fig. 6-12. Typical aircraft actuators.

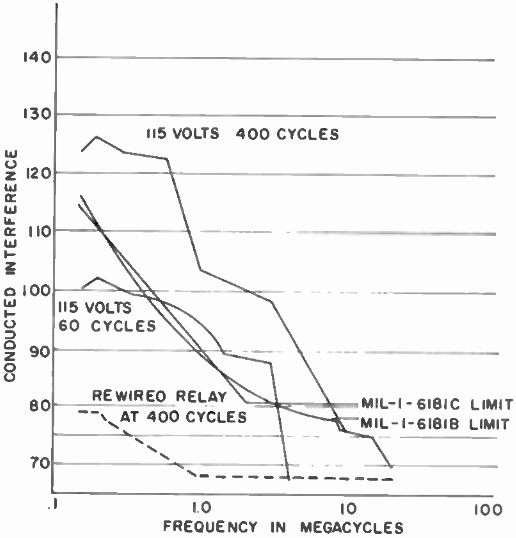


Fig. 6-13. Silicon diode interference at 60 and 400 cps.

voltage is shown at 60 and 400 cps to again illustrate the RF interference voltage of a given diode (TL30A in a 60- and a 400-cps circuit). After the relay is rewired the 400-cps operation produces RF interference voltages far below the permissible limits. The rewired circuit produces no detectable voltages in a 60-cps circuit.

Static power devices such as inverters, converters, and DC transformers produce large RF voltages, often exceeding 1 volt. These devices produce RF interference in this order:

1. Frequency converters—AC to AC.
2. DC transformers—DC to DC.
3. Inverters—DC to AC.
4. Rectifier TR units—AC to DC.

Static devices such as these generally produce RF interference voltage levels many times higher than their earlier rotary equivalent. With the approaches illustrated here, however, these devices can be filtered to meet interference-suppression requirements. Although there is no standard method of suppressing RF interference, proper utilization of the type of diode for a given application, and proper use of control as shown in Fig. 6-11, will produce relatively simple filtering.

CHAPTER 7

Switches and Contactors

Any switching action in an electric circuit generates transients and RF interference. All devices that include switching functions must therefore be considered potential sources of interference. Some of these devices, such as manual switches, are operated so infrequently, however, that the interference they generate generally requires no suppression measures. Others, such as vibrators and some regulators, are operated so frequently and in such rapid succession that their interference is practically continuous. Most switching devices operate somewhere between these two extremes.

The production of rapid changes of current is the essential function of all switching devices; rapid changes of current are likewise the basis of all RF interference. Consequently, the purpose of the suppression system cannot be to eliminate the interference, but only to prevent its transmission to sensitive receivers.

Switching devices can be grouped according to their function. First are regulators, which control the voltage, speed or other characteristic of an electrical system. Next are vibrators, which periodically interrupt the flow of current in order to generate alternating currents or voltages. Finally there are the switches, which are used to start or stop electrical devices.

AC AND DC REGULATORS

Voltage regulators maintain a constant voltage on AC and DC generators. Carbon-pile voltage regulators generate no interference and should be employed whenever possible. They are automatic devices employing variable pressure on a pile of carbon discs to vary the field-circuit resistance of a generator in such a manner that the generator output voltage remains relatively constant. By eliminating the necessity for

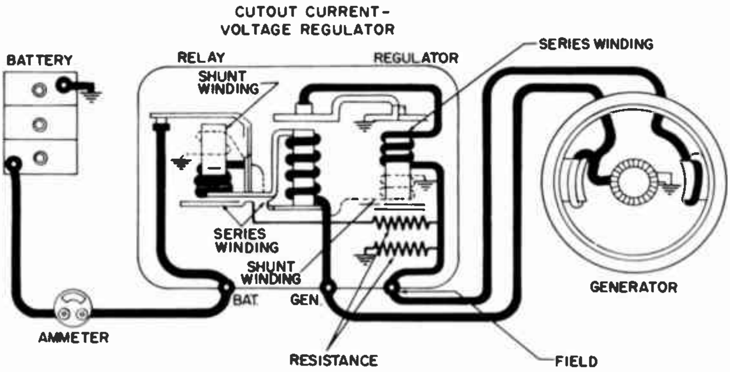


Fig. 7-1. Vibration-type voltage regulator.

contacts that open and close, this type of regulator does away with a major source of RF interference.

The most frequently employed regulator, and the one most important in RF interference suppression, is the electromechanical type. These can be classified into vibrating and rheostatic types. Vibrating types are usually installed in vehicular equipment. Although used to regulate both AC and DC generators, by far their most important application is the regulation of DC systems. A wiring schematic of a typical vibrator-type voltage regulator used in battery charging systems is shown in Fig. 7-1. The regulator has two functions which produce RF interference. One is the make-and-break action of the contact points, with the rapid variation of impedance resulting from arcing. The other is the switching action of the contact points, which causes a transient due to the collapse and surge of voltage. The resistors in the circuit aid in suppressing both sources of interference, in a manner similar to the resistor suppressors in an ignition system. However, they do not eliminate the interference entirely. To do so, shielding and capacitors must be used.

Fig. 7-2 shows a voltage-regulator installation illustrating the application of shielding and capacitors. The shield is mounted with tooth-type lockwashers. The field and armature leads going to the generator are covered with shielding braid to prevent radiation of interference created by the generator as well as by the regulator. A capacitor is connected to the armature terminal of the regulator. The interference at terminal B is residual and is generated by the regulator and bypassed by an additional capacitor. The battery lead, although rather long, does not usually require shielding.

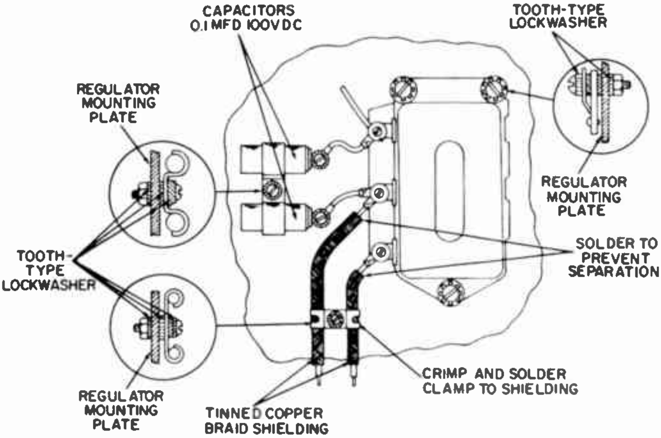


Fig. 7-2. Suppression applied to a voltage regulator.

A good installation for a heavy-duty voltage regulator uses a shield to completely enclose the regulator housing. Tinned copper braid covers the armature and field leads and is terminated in threaded fittings. A bypass capacitor, mounted inside the regulator shield, is connected to the armature terminal. A feedthrough capacitor is mounted through the regulator shield in the battery lead.

The voltage regulator should be installed as close to the generator as possible, to minimize shielding of interconnecting wiring. The preferred installation is to mount the regulator directly onto the generator, with the interconnecting wiring and the generator terminals completely enclosed within the

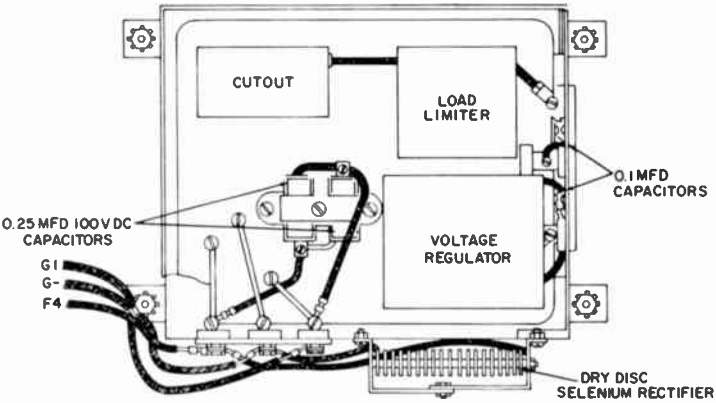


Fig. 7-3. Voltage suppression using dry-disc selenium rectifiers.

regulator shield. When this is done, there is no need for shielding braid. A bypass capacitor is connected to the armature terminal and mounted inside the shield; a feedthrough capacitor, connected to the battery terminal, is mounted through the regulator shield. Fig. 7-3 illustrates an alternate suppression system for a voltage regulator using a dry-disc selenium rectifier.

Vibrating-type regulators are also used to automatically regulate the voltage output of an alternator. The interference generated (arcing at the contacts and the resulting transients) by the AC regulator is similar to that generated by the DC regulators. The suppression systems are basically identical, consisting of capacitors and shielding. The regulator is shielded with a capacitor that bypasses interference from the lead to the field rheostat. The input lead from the exciter is shielded; and a bypass capacitor, mounted inside the shield, is connected to the regulator terminal.

The other frequently used AC-generator voltage regulator is the direct-acting rheostatic type. It, too, controls the voltage by varying the resistance in the exciter field (sometimes in the generator field circuit). A movable arm directly controls the closing and opening of a set of contacts. Thus the amount of regulating resistance in the exciter shunt-field circuit is adjusted automatically.

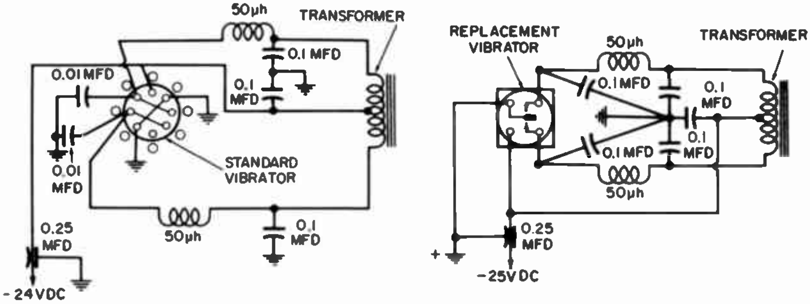
Because this type of regulator operates only when there is a change in the load and when a voltage correction is necessary, the interference generated is much less severe than from the vibrating type. The major consideration for interference suppression is the prevention of conduction interference into the regulator circuits from the exciter. Adequate suppression of the exciter eliminates this danger.

VIBRATORS

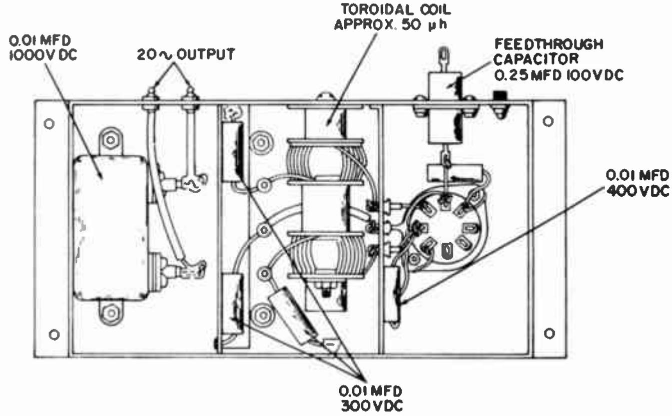
Vibrators are electromechanical devices for converting a direct voltage into an alternating voltage. Vibrators contain armatures that reverse the direction of current flow during each vibration. They are used extensively in the power supplies of auto radios and other portable equipment, to convert the voltage of a storage battery into a low-frequency alternating voltage that can be stepped up by a power transformer, rectified, and filtered.

The waveform of the alternating voltage produced by a vibrator is more nearly rectangular than sinusoidal. Consequently it is rich in harmonics that are capable of causing a lot of RF interference. If at all possible, vibrators should not be used whenever RF interference must be minimized. When it is necessary to use vibrators, complete shielding and feedthrough capacitors or filters must be employed.

Fig. 7-4 shows the suppression system applied to the vibrator in a 20-cps ringing converter. A pi-type filter network is connected onto each line to the transformer. A feedthrough capacitor on the DC input prevents the DC line from conducting the interference generated by the vibrator. In addition, capacitors are installed just before the point where the output leads exit from the shield. This is on the high-voltage side of the transformer (not shown). Any residual interference is thus bypassed to prevent possible coupling back into the leads after it has been removed.



(A) Circuits.



(B) Assembly.

Fig. 7-4. Suppression for a 20-cps ringing converter.

MANUAL AND AUTOMATIC SWITCHES

Switches are devices for completing, interrupting, or changing the connections in an electric circuit. Examples of manual switches are ignition (battery systems) and magnetic shutoff types. Typical automatic switches are relays, governors, and voltage regulators.

Usually, manual switches are operated so infrequently that they are not important interference sources. In most instances, however, manual switches can serve as antennas by radiating interference that the switch wiring has conducted from an interference source.

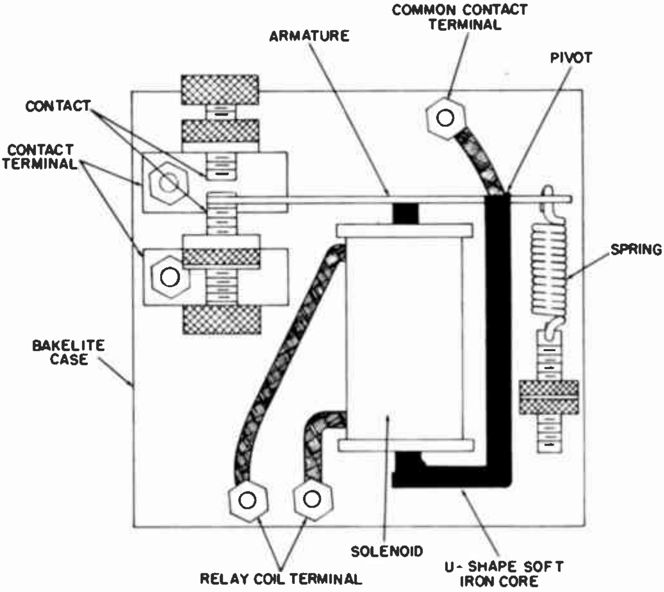


Fig. 7-5. A typical relay.

Automatic switches are serious generators of interference because of the frequent opening and closing of their contacts. Unlike a manual switch, an automatic switch opens and closes dozens or even hundreds of times each second and thereby generates a steady, high level of interference.

Of all automatic switches, relays are the worst offenders as RF interference sources. The most frequently used relay is the electromechanical type. It uses the change of current in one circuit to actuate an electromagnet and move an armature that opens or closes contacts to produce a change in the electrical condition of another circuit. The principal components of an electromechanical relay are the relay magnet, which consists of a coil and iron core; the armature, which is attracted by the magnet; and the contact points, which are actuated by the armature. Fig. 7-5 shows the construction of a typical relay.

Three sources of interference in the action of a relay are voltage surges, arcing, and mechanical bouncing. Voltage surges are caused by abrupt interruption of the current flow as the contact points open. Typical relay coils have a high ratio of inductance to distributed capacitance; when the current is interrupted, the magnetic field about the relay coil collapses, inducing a voltage often a hundred times greater than the supply voltage across the coil. Because of their steep wavefronts, these voltage surges are severe sources of interference.

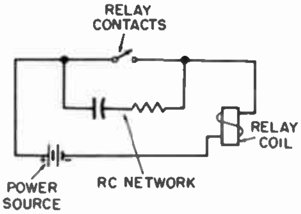
The second source of interference is arcing at the contact points. In addition to causing errosion of the points, arcing produces rapid variations of impedance that result in high-frequency transients.

The third source of interference, mechanical bouncing, occurs as the contacts meet in the process of closing. The repetitive closures and interruptions of current cause a series of transients.

To suppress the interference resulting from relay action, shielding, resistance-capacitance networks, varistors, selenium rectifiers, or filters may be used. Shielding is impractical in most relay installations. In teletype equipment for example, where there are many relays, shielding would be excessively heavy and expensive. However, where only a few relays are involved, shielding of the unit and filtering of the leads—to prevent conduction along the associated wiring—may be practical.

A method of reducing the voltage surge and the subsequent arcing across the relay contacts is to insert an RC network across them, as shown in Fig. 7-6. When the contact points open, the energy stored in the coil is dissipated through the RC network, preventing the sudden collapse of the magnetic field and reducing the induced voltage. In addition, the resistance helps damp out any oscillations. A capacitor should never be connected across the contacts without including a series resistance, because the discharge of the capacitor when the contacts are closed can cause a heavy surge of current. In addition, a capacitor alone may change the circuit characteristics sufficiently to interfere with normal operation of the

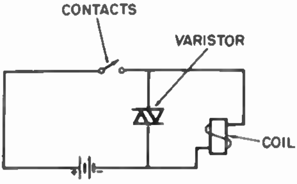
Fig. 7-6. RC network in a relay circuit.



relay. For example, increasing the release time of the relay. RC networks are cheap, small, and easy to use. Even though they increase the operating time of the relay, their performance compares favorably with that of other voltage surge suppressors.

Silicon-carbon varistors and selenium rectifiers are also used as voltage surge suppressors. A silicon-carbon varistor, connected across the terminals of an inductance coil, acts to limit the surge voltage generated when the circuit is opened. Varistors exhibit a nonlinear relationship between voltage and current; when the voltage is high, the resistance of the varistor drops accordingly, providing a path for the current to flow

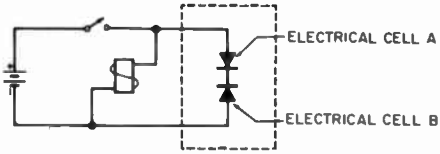
Fig. 7-7. Varistor in a relay circuit.



through the varistor and be dissipated through the closed circuit of it and the coil. This prevents the magnetic field of the coil from suddenly collapsing, and the subsequent high induced voltage. At low voltages, the resistance of the varistor is too high to affect circuit operation. Fig. 7-7 shows a relay circuit with a varistor installed. In limiting voltage surges, the varistor also decreases the danger of arcing at the contact points.

A recent development is the use of selenium rectifiers as voltage surge suppressors. These use a characteristic of selenium cells that has been considered a disadvantage in recti-

Fig. 7-8. Selenium rectifiers in a relay circuit.



fier applications. The selenium cell exhibits a decreasing resistance as the voltage increases in the blocking direction. Fig. 7-8 shows the application of selenium rectifiers as voltage surge suppressors in an AC-DC relay circuit. As the self-induced voltage builds up across the relay coil, following the opening of the contacts, cell B momentarily presents a low-resistance path that prevents the induced voltage from rising to a destructive sparking potential. As the energy is dissipated in the resistance of the selenium cell and coil, the induced voltage drops rapidly and the reverse resistance of the cell increases by 20,000 to 40,000, thus quickly damping the current in the coil. The speed of damping is shown by the 10.5-millisecond release time of the protected relay. Cell A, which has the supply voltage impressed across it in the blocking direction, effectively prevents current flow through the voltage surge suppressor. Practically no energy is taken from the power source by the suppressor. Because of its back-to-back construction, it performs well on both AC and DC installations. It is easily installed, requires little space, and increases the life of the relay contacts.

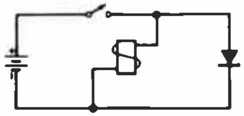


Fig. 7-9. Half-wave surge suppressor.

Fig. 7-9 shows a half-wave rectifier connected for surge suppression in a DC circuit. The rectifier blocks the flow of current from the battery used to energize the coil, but offers a low-resistance path when the current path is broken. The self-induced voltage for this surge suppressor is very low; however, the release time of 55 milliseconds is excessive for many applications.

The use of filters has little effect on reducing the voltage surge, but suppresses the interference by preventing it from being conducted along the associated wiring and eventually radiated.

CHAPTER 8

Suppression Techniques

Proper bonding, and installation of bypass capacitors, account for more than two-thirds of all corrective measures applied to equipment which fails to meet minimum standards of RF-interference suppression. This shows the importance of these two items in the design and installation of RF-interference systems. The components and materials required for proper bonding and bypassing are also the most common ones and therefore easiest to obtain.

Other suppression measures common to many installations are filters, shields, and resistor suppressors. Filters bypass the RF interference currents in much the same way as capacitors. Since, in most cases, capacitors are sufficient to properly suppress the interference, filters are not used except for special applications. Resistor suppressors are effective, but are limited mainly to ignition systems. Shielding, although cumbersome and expensive, is always necessary to attenuate high-frequency interference from strong sources such as distributors and their ignition-system components, and from effective radiators such as interconnecting leads in ignition systems and similar installations. Existing shielding—such as that afforded by housing, dust covers, or partitions—is an excellent means of augmenting a suppression system. Moreover, in many cases of severe interference sources there are other suppression means of equal effectiveness available.

BONDING

As far as RF interference is concerned, bonding serves one principal purpose—to provide a low-impedance path for the RF interference currents. A necessary condition for a good bond is very low DC resistance. On the other hand, because of the importance of inductance and capacitance at radio frequencies, low DC resistance does not necessarily assure a good bond. A very low inductance and proper installation, where care is taken lest the system capacitance combine with the bond inductance and produce a very high impedance, are also of considerable importance. Yet, because of the difficulties in measuring RF impedance of bonds, the DC resistance is used as a measure of the effectiveness of the bond.

There are two bonding applications where the foregoing does not apply. One is the use of conductive drive belts to prevent the accumulation of charges, which may lead to high voltages. The high voltages, in turn, may cause electric discharges and RF interference. Such charges accumulate as a result of the friction between the belt and pulley. In this case, no RF interference currents need pass through the bond, and the DC resistance is the only criterion. Nor is it necessary that this resistance be very low. Generally the resistance between diametrically opposite points of a belt should be no more than about 0.2 megohm when the belt is slack, and no more than 0.3 megohm when it is under tension. The other application where a low impedance is not particularly important is the use of bonds for the prevention of sparking between members making intermittent contact during vibrations. Here, a bond of even moderately high impedance will prevent the development of potential differences high enough to cause sparking.

Two types of bonding can be distinguished—direct bonding, and bonding by means of jumpers. Direct bonding consists of a permanent or semipermanent metal-to-metal contact between the members. If practical, this method is always preferable. But if clearance between the bonded members must be maintained for mechanical reasons, or if the equipment to be bonded is shock-mounted, then bond straps are the only alternative. At best, a bond strap is a poor substitute for a direct bond.

A special problem arises when the two members to be bonded are in motion. To bond a generator shaft to the generator housing, for example, obviously neither direct bonding nor bond straps are feasible.

Direct Bonding

Direct bonding is accomplished by direct metal-to-metal contact under high and uniform pressure, or by fusion of the adjoining surface layers. If properly constructed, a bond of this type has low DC resistance as well as low RF impedance. Permanent joints of metallic parts made by welding, brazing, or sweating are the best direct bonds. Semipermanent joints of machined metallic surfaces, rigidly held together, provide excellent direct bonds if the contact areas are clean and all protective coatings have been removed before assembly.

Semipermanent bonds may eventually corrode. While corrosion is a very complicated process, the most important factors are the amount of moisture present and the relative positions of the two metals in the so-called "electromotive-force" series (comprising magnesium, aluminum, zinc, chromium, iron, cadmium, nickel, tin, lead, copper, and silver). The more moisture present and the farther apart the two metals are in the electromotive-force series, the more severe the corrosion will be.

When two different metals are in contact, the one lower in the electromotive-force series will be more affected by corrosion. Consequently, the part that is more easily replaceable should be made of the lower metal. This is the reason why cadmium-plated washers are recommended with steel or iron surfaces.

The decision as to whether or not a surface is clean is often a difficult one. A surface may appear physically clean when wiped with a clean cloth, and it may be chemically clean when subjected to alkaline cleansers such as solvents or chromatic acid. Nevertheless, it may not be clean enough to assure good electrical contact, because of the presence of layers of invisible oxides or other substances that are not removed by the foregoing procedures. This difficulty is particularly severe where considerable time elapses between the completion of a part and its bonding, as is frequently the case with RF-interference suppression components. Experience shows that the use of tooth-type lockwashers effectively and economically overcomes this difficulty because the teeth can cut through any surface layers and into the metal. Typical methods of bonding with tooth-type lockwashers are shown in Fig. 8-1. Washer A is the external type; washer B the internal type; and washer C, most frequently recommended, the internal-external type. Such washers are widely used in suppression systems and are available in a wide variety of types and sizes.

Bond Straps

The length of a bond strap connecting two members introduces an inductance which is much larger than that of a direct bond. This inductance is small enough to be of no importance at power frequencies. But even an inductance as low as 0.01 microhenry has an impedance of about 6 ohms at 100 mc, and this impedance cannot be ignored in many applications. In fact, most bond straps have larger inductances than this. The measured RF impedance of typical flat and round bond straps at frequencies up to 30 mc is shown in Fig. 8-2. Note that the impedance increases almost linearly with frequency, hence is due almost entirely to the inductance of the strap.

An additional difficulty is introduced by the everpresent capacitances between the bonded members; these capacitances are in parallel with the inductance of the strap. The impedance of a parallel combination of inductance and capacitance is very

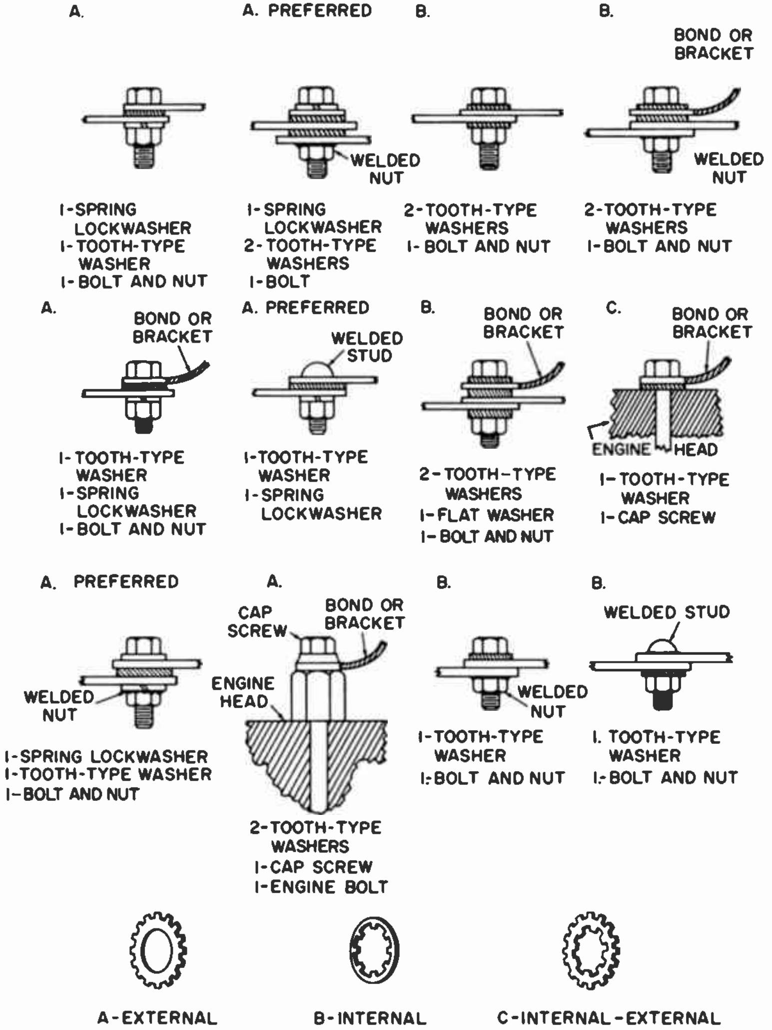


Fig. 8-1. Typical bonding applications of tooth-type lockwashers.

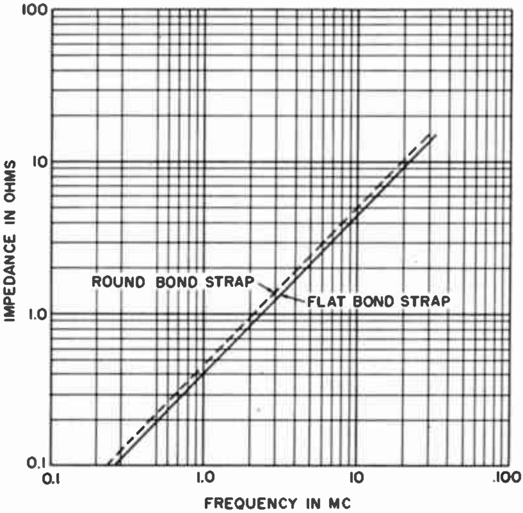


Fig. 8-2. Impedance of flat and round bond straps.

high at certain frequencies; in many applications these frequencies lie between 50 and 500 mc, which is well within the region of RF-interference considerations. These effects can be reduced by keeping the inductance as low as possible—which in turn requires the use of straps of minimum length and having a high ratio of width to thickness. Another important consideration is good direct bonding between the straps and the members to be bonded.

Fig. 8-3 shows a typical shock-mounted bonding-strap application. It is used with all shock-mounted equipment which is a potential source of interference. Even more important, it is used with all shock-mounted receivers for which a good bond to ground is especially important.

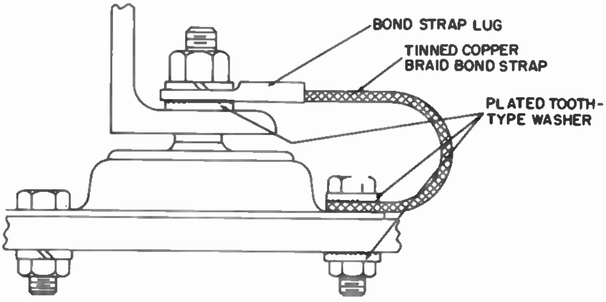


Fig. 8-3. Typical shock-mounted bond.

A typical use of bond straps is for bonding structural parts of a vehicle which cannot be bonded directly for mechanical reasons. Another example is a shock-mounted engine.

It should be emphasized that screw threads are never considered adequate bonding surfaces. Sheet-metal screws, in particular, are wholly inadequate. If two structural members are held together by screws, the impedance between them is usually comparatively high unless good direct contact is maintained. Where bonding is required, all efforts should be made to ensure good direct bonding. Otherwise, bonding straps must be used.

BYPASS-CAPACITOR AND FILTER INSTALLATION

The purpose of bypass capacitors and filters is to prevent radiated and conducted interference from reaching sensitive receivers. They achieve their purpose by introducing a high impedance into the path of the interference currents, or by shunting them to ground through a low impedance. Since the circuits into which they are inserted are designed to carry power, control, or signal currents, they must affect as little as possible the normal circuit operation.

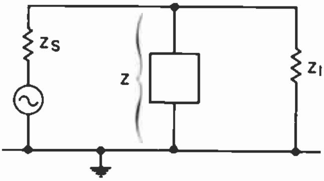
The effectiveness of suppression elements can be measured in terms of their impedance. However, the insertion-loss type of measurement is more practical because the effect of other impedances in the circuit is also important. Referring to the circuit of Fig. 8-4, the insertion-loss ratio is defined as the ratio of the voltages across load impedance Z_l before and after the suppression element is inserted into the circuit. The insertion loss is usually measured in db, which is found by multiplying the common logarithm of the insertion-loss ratio by 20. The insertion loss is a function not only of the suppression element impedances, but also of load impedance Z_l and source impedance Z_s. If, however, the suppression system is a single shunt element of impedance Z, and if Z is much smaller than Z_s and Z_l (as it usually is at the frequencies of interference currents), then the insertion-loss ratio is almost inversely proportional to impedance K, and either impedance or insertion loss may be taken as a measure of effectiveness. For test purposes, impedances Z_s and Z_l are standardized, usually at 50 ohms each, so that the effectiveness of different systems may be compared.

An ideal capacitor would contain nothing but pure capacitive reactance, and its impedance would be inversely proportional to the frequency. But in a general-purpose suppression capacitor, the interference frequencies normally are much higher than those of the power or control currents for which the system was designed. Thus, the presence of a high-impedance element in shunt does not impair normal operation of the equipment, while at radio frequencies the low impedance shunts the interference currents to ground.

All practical capacitors must contain both resistance and inductance in addition to capacitance. For this reason, their characteristics deviate from those of the ideal capacitor. The degree to which the ideal is approached depends on their construction and installation.

The inductance of a practical capacitor causes its impedance to decrease with frequency until a minimum is reached, and then to increase again. The frequency at which the minimum occurs is called the resonant frequency, and the impedance at the resonant frequency is the resistance of the capacitor. Consequently, the insertion loss reaches a maximum at the resonant frequency and then decreases. This means that a capacitor ceases to be an effective bypass element at frequencies much above its resonant frequency.

Fig. 8-4. Circuit for measuring insertion loss.



If capacitors were ideal, their effectiveness as shunt elements would be greater as their capacitance was increased. In actual capacitors, however, three considerations limit the value of capacitance used in a suppression element. The first is the inductance, which usually increases with the size of the capacitor. Since the resonant frequency is increased by decreasing the inductance, the use of a smaller capacitance increases the high-frequency effectiveness. Thus, although an ideal capacitor of 1-microfarad capacitance would be ten times as effective in bypassing RF interference currents as a capacitor of 0.1 microfarad, in practice the smaller capacitor is likely to be the most effective at higher frequencies.

The second consideration that limits the size of bypass capacitors applies only to AC circuits and is the amount of power current drawn by the capacitor. The impedance of a 1-mfd capacitor at 60 cps is about 2650 ohms. In a 500-volt system, this capacitor would draw almost 200 ma of current, which may well be considered an excessive drain. Therefore, the capacitance would have to be reduced to a value that makes the current drain negligible, such as 0.1 or even 0.01 mfd, depending on the particular installation.

The third consideration applies to relays, vibrators, and other devices in which the deterioration of contact or breaker points is important. The use of optimum-sized capacitors is here frequently prohibited by their adverse effect on the life of the contacts or breaker points.

Bypass Capacitors

The construction of a typical bypass capacitor is shown in Fig. 8-5. Its inductance is made up of the internal inductance of the rolled capacitor section, and the external inductance of the capacitor lead. The smaller the total inductance, the higher the resonant frequency and hence the larger the useful frequency range. Therefore, both the internal and external inductances should be kept to a minimum. For a given capacitor, the internal inductance is fixed, but the external inductance can be reduced by keeping the pigtail lead as short as possible. The effect of the length of this lead is shown in Fig. 8-6, where insertion loss is plotted against frequency for different lead lengths. It is clear that even with the lead length reduced to one-quarter inch, the capacitor becomes rather ineffective above 10 or 20 mc, indicating that this frequency limit is imposed by the internal inductance rather than by the external lead, which obviously cannot be shortened to much less than a quarter inch.

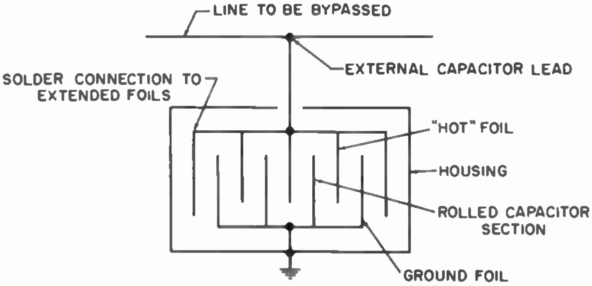


Fig. 8-5. Construction of a typical bypass capacitor.

Feedthrough Capacitors

A design which considerably reduces the internal inductance and eliminates entirely the external inductance is the feedthrough capacitor. Its construction is shown in Fig. 8-7 and its insertion loss is plotted versus frequency in Fig. 8-8, together with the characteristics of a lead-type capacitor and an ideal capacitor of identical capacitance. The superiority of the feedthrough type at frequencies above 10 mc is apparent.

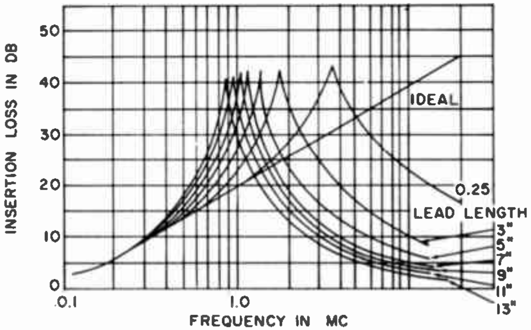


Fig. 8-6. Insertion loss of a .05-mfd capacitor with various lead lengths.

Since a feedthrough capacitor must carry all of the line current through its center conductor, it must be rated not only in terms of its capacitance and the voltage it has to withstand, but also in terms of the current it can safely carry.

Filters

Filters, which are more complicated and expensive than capacitors, combine the bypassing action of capacitors with the impeding action of inductors. Properly chosen filters provide greater insertion loss than bypass capacitors over the frequency range for which they are designed. The most frequently used filters are low-pass types with cutoff frequencies from 1 to 10 kc. These filters have a very small insertion loss for DC

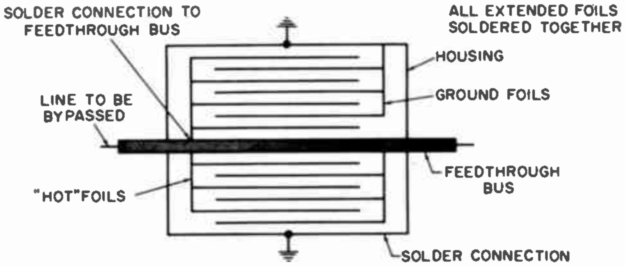


Fig. 8-7. Construction of a feedthrough capacitor.

and ordinary power frequency currents, and greatly attenuate all RF interference currents.

Since filters contain capacitances as elements, the inherent inductance of a capacitor is a limiting factor here also. Moreover, filters also contain inductance coils, the distributed capacitances of which impose further limitations on the design. It is possible, however, to take these stray elements into consideration during the design, so that a well-designed and carefully constructed low-pass filter will remain effective as a suppression element well above 100 mc.

Special filters are sometimes useful in the solution of specific RF-interference problems. Bandpass filters, which allow a certain band of frequencies to pass and suppress all others, are sometimes used in the antenna circuit of receivers in order to increase their selectivity and improve their interference rejection. They may also be used in the output circuits of transmitters or oscillators, to suppress harmonics and other spurious frequencies. Band-elimination filters, which suppress a certain band of frequencies and pass all others, are used where the interference to be suppressed contains only a narrow band of frequencies, such as from a radar modulator.

High-pass filters which suppress all frequencies below a certain cutoff frequency are rarely used as suppression components.

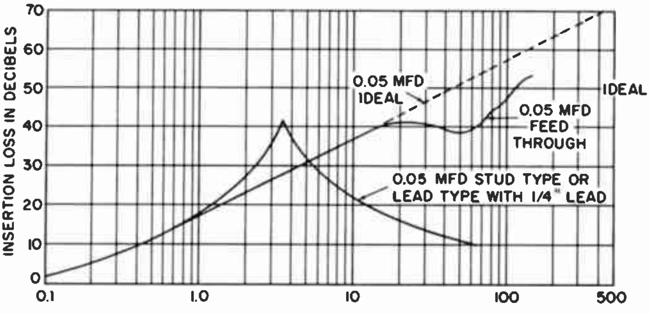


Fig. 8-8. Insertion loss of a feedthrough capacitor.

Installation Principles

The principles to be followed in installing suppression components are identical for filters and capacitors. The lead from the interference source to the suppression element carries interference currents, and the impedances of the connections to the element and from the element to ground are in series with the bypassing portion of the element. Consequently, the

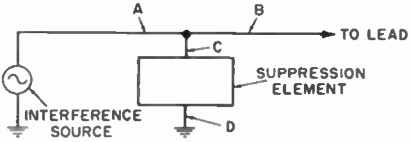


Fig. 8-9. Installation of a suppression component.

suppression component must be installed as close to the source as possible so that lead A (Fig. 8-9) is as short as possible, and all other leads (in particular, output lead B) must be kept far away from lead A. In severe cases of interference, lead A should be shielded. In addition, lead C, if used, must be as short as possible and the ground connection D must be a very low impedance. (Lead C is not used if the suppression element is a filter or feedthrough capacitor.) This means that good bonding is most important in the installation of filters and capacitors.

In almost all suppression capacitors, the outer housing is used as ground so that proper installation can make the impedance of ground connection D negligible. In addition, in the feedthrough capacitor, lead C is entirely absent. Thus, all excess series elements are practically eliminated. This, together with the characteristics described earlier, are the main reasons for the superiority of feedthrough capacitors over those with standard leads.

A typical installation of a bypass capacitor is shown in Fig. 8-10. When two such capacitors are used close together, a double clamp provides convenient mounting as shown in Fig. 8-11. Feedthrough capacitors are most effective when mounted directly in a shield. Fig. 8-12 shows feedthrough capacitors installed in conjunction with a shield. However,

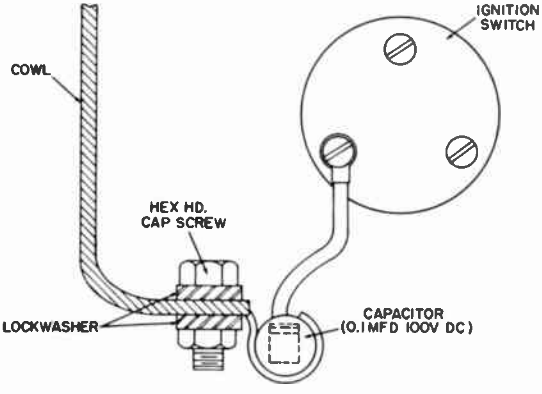


Fig. 8-10. Typical byass-capacitor installation.

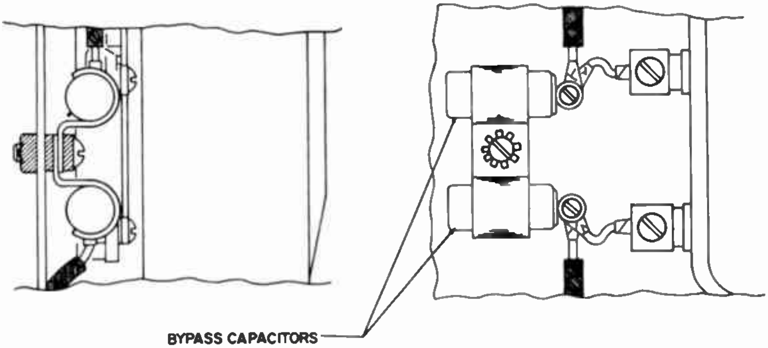


Fig. 8-11. Typical installation using double capacitor clamp.

feedthrough capacitors, because of their superior characteristics, are recommended even when mounting in a shield is not feasible.

A typical filter installation is shown in Fig. 8-13. The filter and the leads to it are fully shielded to utilize to the fullest extent the filter suppression capabilities.

Ferrites in RF Interference Filters

Basically, ferrites are bivalent iron-oxide compounds. These materials have high permeabilities and high resistivities. Ferrites resemble ceramics in production processes and physical properties; they exhibit extremely high effective dielectric constants and comparatively low saturation flux densities. The Curie point ranges from 100° to 300° C.; the basic properties of ferrites classify them as semiconductors.

The permeability of ferrous magnetic materials generally increases with frequency, and losses are higher for higher per-

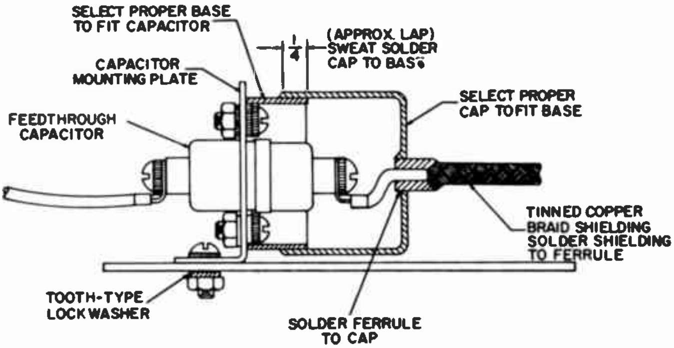


Fig. 8-12. Feedthrough capacitor shield assembly.

meabilities. This is qualitatively true also for ferrite materials. Ferrites were developed primarily for their low losses at high frequencies, compared with laminated or powdered-iron cores. Electrical conductivity is very low; therefore, eddy-current losses are negligible.

The effect in ferrites of the combination of high permeability and a high dielectric constant causes the propagation velocity of electrical energy within the material to be very low compared with the velocity in air. This reduction in propagation velocity leads to resonance within dimensions much smaller than those for resonance in most other materials. This dimensional resonance is generally accepted as the cause of unusually high power losses at frequencies above the critical frequency. Since the material in a ferrite core is not homogeneous, the critical frequency is not sharply defined, and the losses tend to be large over a broad band of high frequencies.

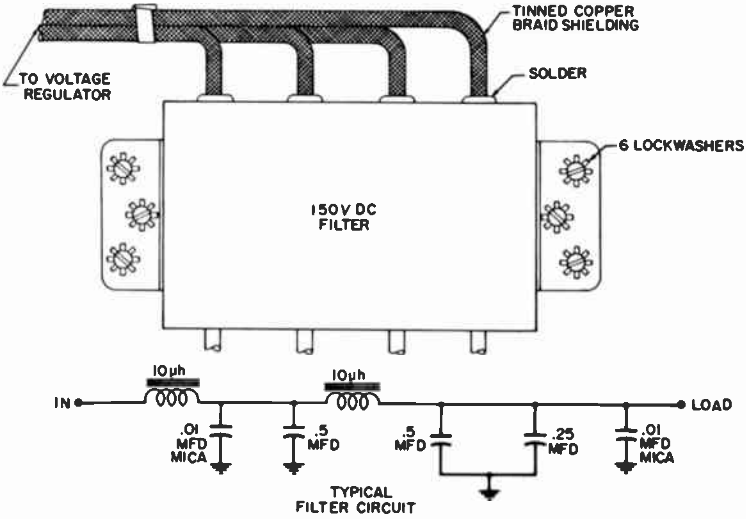


Fig. 8-13. Typical filter installation.

Since the resistivity is high in ferrites, eddy-current losses are negligible up to the higher radio frequencies; however, high loss of effects occurs even at lower frequencies. For example, the wavelength of a 2-mc electromagnetic wave in a *Ferroxcube III* core is approximately two centimeters, as opposed to 15,000 centimeters in air. Because of this shortened wavelength, the ferrite components are of the same size as the guide wavelengths and, as a result, dimensional effects occur.

Hysteresis, eddy currents, and dimensional resonance make up some of the better-known ferrite losses, but still other loss phenomena occur. Additional ferrite losses have been attributed to domain-wall relaxation and ferromagnetic-resonance effects. (Domain-wall relaxation is the interaction between the spinning electron's angular momentum crystal forces, and damping factors. Ferromagnetic resonance occurs when the precession frequency of the electron equals the frequency of the applied field.)

Since ferrites have loss mechanisms due to hysteresis, eddy currents, dimensional resonance, domain-wall relaxation, and ferromagnetic resonance, it is desirable to use these effects for a compact low-pass filter.

The most basic low-pass filter is a series inductor. Ideally, the impedance it generates increases linearly with frequency. The actual impedance versus frequency characteristic for an inductor depends on a number of factors. Interturn capacitance and capacitance to ground affect the value of inductive reactance. Since the ferrites have core loss mechanisms, the impedance can become quite resistive for ferrite-core inductors as the frequency increases. The basic physical inductive configuration for use in filters is a toroid of rectangular or circular cross section.

Impedance of Ferrite-Core Coils

At frequencies sufficiently high to require consideration of core losses, the impedance of a coil will not be a pure reactance. The actual impedance must be expressed as a complex number and will have a phase angle approaching +45° as the frequency increases. The effective permeability also is a complex number, with its real and imaginary parts directly related to the reactance and resistive components of the complex coil impedance, respectively. The components of permeability or impedance are not constants; both depend on the physical dimensions of the core, the product of permeability and dielectric constant, and frequency. For a given core and fixed magnetizing field, the only remaining variable is frequency. The relationship between frequency and coil impedance must be determined experimentally.

When ferrite cores are in the form of shielding beads, the conductor normally passes through each core only once. For larger cores, more turns can be used. If the cores are not magnetically saturated, the complex impedance at any frequency will be in direct proportion to the total volume of the cores and to the square of the number of turns on each core.

The impedance of a short length of wire threaded through one or more cores can be measured on an RF bridge, and the measured values applied to other configurations involving different numbers of cores of the same dimensions. Likewise, measurements can be extended to cores having other numbers of turns, within the limits imposed by interturn stray capacitances.

Fig. 8-14 illustrates the relationship of core losses to frequency for several ferrite cores. The losses are expressed as the resistive component of coil impedance and can be measured on an RF impedance bridge. Curve A is for a single turn on a washer of material A; this ferrite has the highest permeability of any of the ferrite cores illustrated here. Losses reach a peak for this material at about 6 mc. The resistance remains at 40 to 50 ohms at all higher frequencies within the limits of the RF bridge. The second rising portion of the loss characteristic is caused by dimensional resonance within the smaller core dimension.

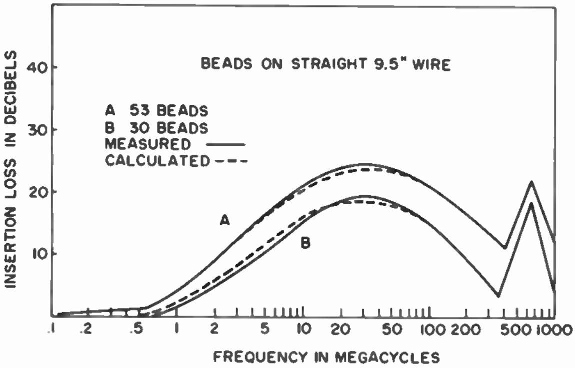


Fig. 8-14. Insertion loss of shielding beads.

Curve B of Fig. 8-14 shows the losses in a toroid of material B; this core is longer and slightly thinner than washer A. For this reason, the two possible resonant frequencies of material B are separated further. Since the permeability is less than that of material A, the first resonance occurs at a higher frequency in material B than in material A.

Ferrite Filter Applications

The simplest application of ferrites in a filter is to thread the conductor carrying RF interference through a number of shielding ferrite beads in order to produce a frequency-sensitive series impedance. This impedance will have a large resistive component; therefore it will absorb a portion of the undesired RF interference energy and lessen the danger of radiation. If this element is inserted between 50-ohm input and load impedances for insertion-loss measurements, the insertion loss, I_L, at a given frequency will be:

$$20 \log_{10}(100 + n\Delta R + j\, n\Delta X)/100$$

where,

n is the number of beads,
R is the increment of resistance of one bead at a given frequency,
X is the increment of inductive reactance at a given frequency.

For example, suppose 30 Type 3C shielding beads are used and it is desired to find the insertion loss at 20 mc. The values of ΔR and ΔX are 23 ohms and 14.4 ohms respectively, from curves C of Figs. 8-15 and 8-16. The insertion loss will then be:

$$I_L = 20 \text{ Log}_{10}[100 + (30)(23) + j\,(30)(14.4)]/100$$
$$= 19.04 \text{ DB.}$$

Fig. 8-14 illustrates the insertion-loss characteristics of two such filters; curve A is the insertion loss of 53 beads on a 9.5-inch length of wire, and curve B is for 30 beads. The insertion loss at 20 mc is exactly as calculated in the example given for curve B. A filter of such a length normally is not practical; the electrical length of the wire is increased by the presence of the beads. Therefore, periodic dips and peaks occur in the insertion-loss characteristics. The most advantageous use of this simple filter appears to be in applications requiring only small amounts of isolation.

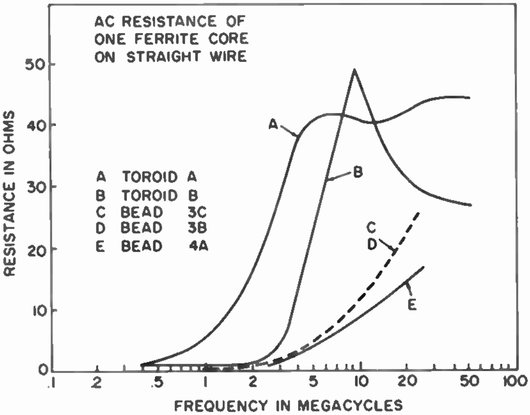


Fig. 8-15. Measured resistance of ferrites.

As the number of beads in a string is increased, the effectiveness of each additional bead becomes smaller. Thus, to double the insertion loss obtained from 30 beads, 300 beads is required because of the logarithmic nature of the insertion-loss formula. In addition, the first dip of the insertion-loss curve would occur at a much lower frequency. There would be no appreciable change in the cutoff frequency of the filter because this is determined primarily by the dimensions of the individual beads.

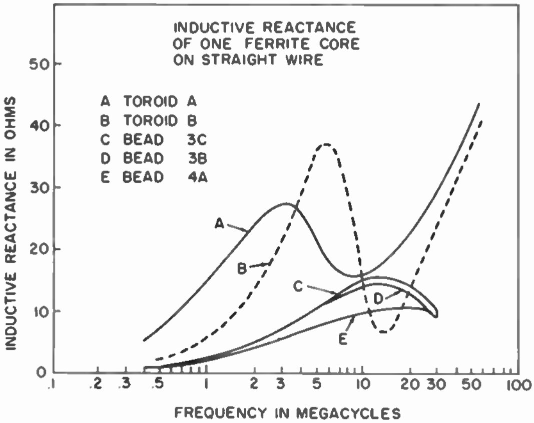


Fig. 8-16. Measured inductive reactance of ferrites.

Shielding beads, or larger ferrite cores, can also be used as series elements in low-pass pi- or T-filter networks, or in various combinations of half-sections.

SHIELDS

The purpose of a shield is to confine all RF-interference energy within a specified region, or to prevent such energy from entering. The first type of shielding is used for ignition systems, motors, and other sources of RF interference, and the second type for receivers or leads to receivers.

Because power or control energy must always be supplied or removed from a region within the shield, and because the techniques of construction as well as the necessity for accessibility and serviceability demand that shields be made of more than one part, openings, seams, joints, or other discontinuities will always be present. The problem of constructing an effective shield has therefore two separate phases: One is prevention of the penetration of electromagnetic energy through the shielding wall itself, and the other the prevention of the penetration of electromagnetic energy through the discontinuities in the shield. The second requires the greater consideration. A shield is no more effective than its poorest joint.

Shielding Materials

The problem of preventing penetration through the shield itself is comparatively simple. Under certain simplified conditions, the ratio of the electromagnetic energy that has penetrated a shield to that entering it, expressed in db, varies inversely as the thickness and square root of the magnetic permeability, and directly as the square root of the resistivity. While shielding effectiveness depends on such other factors as the impedance of the wave and the geometrical shape of the shield, the dependence on these other quantities can be completely ignored, provided the three factors mentioned previously are correctly chosen. This leads to walls that may be much thicker than necessary for mechanical reasons alone whenever the shield must support itself.

The shielding effectiveness of a solid metal wall increases with frequency (except possibly for magnetic materials). Therefore measurements of this effectiveness need be made only at the lower frequencies. In fact, if a particular material and thickness are satisfactory below 20 mc, they will be satisfactory above that frequency. This condition may be vitiated, however, by the effect of seams, joints, or other discontinuities. For them the opposite is true; their shielding effectiveness decreases with frequency so that joints which are entirely satisfactory at low and medium frequencies may be quite leaky at high, very high, or ultra-high frequencies.

Instead of solid walls, meshes of metal wires are sometimes used for shielding purposes. The attenuation of an electromagnetic wave in a mesh is considerably less than in a solid shield. Therefore, the principal shielding action of a mesh is due to reflection. Mesh with 50% open area and 60 or more strands per wavelength, for instance, introduces a reflection loss nearly equal to that of a solid sheet of the same material. For this to be true, however, the mesh must be so constructed that the individual strands are permanently joined at their intersection by some fusing process that makes good permanent electrical contact.

Performance Measurement of Shielding Materials

Since one of the purposes of a shielded enclosure is to provide a region which is free as possible from electromagnetic fields, the walls of the enclosure must reflect and attenuate the fields which impinge upon them. This is true also of an enclosure which is used to prevent energy from leaving the vicinity of the source. Over a wide range of frequencies, the fields will be due to plane waves traveling to the enclosure. This results in the need for an instrument capable of measuring the effectiveness of shielding materials to electrostatic fields having the impedance of plane waves.

The field of the TEM mode in a coaxial transmission line forms a structure suitable for testing the shielding effectiveness of materials to plane-wave impedance fields. The results of such tests can then be used to predict the shielding effectiveness under other conditions. To accomplish this, a lamina of the material to be tested is inserted into the line to act as a barrier extending from the inner to the outer coaxial conductors and perpendicular to them, as indicated in Fig. 8-17. This lamina acts as a barrier to waves traveling through the line.

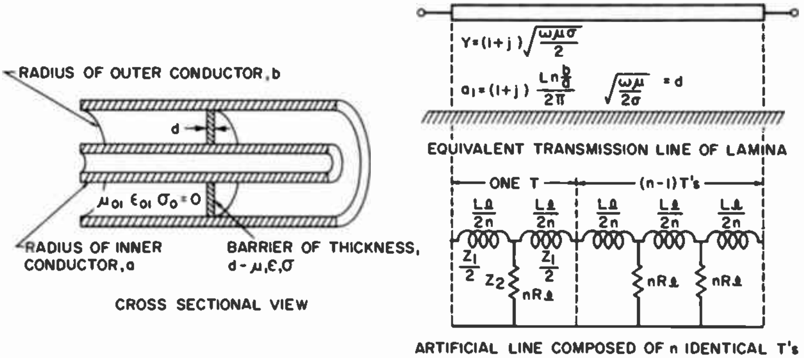


Fig. 8-17. Coaxial testing device.

The shielding effectiveness of the material comprising the lamina is given in terms of the ratio of the amplitude of the wave which penetrates and reaches the detector, to the amplitude of the wave which leaves the source and impinges upon the lamina. The voltage across the coaxial structure is the time integral of the radial electric field; consequently, measurements of voltage across the coaxial line are equivalent to measurement of the electric-field intensity. The advantage of using a coaxial structure to test the shielding effectiveness of materials is that the fields are confined and geometrically simple. The coaxial method of testing also serves to evaluate the electrical parameters of a screening material.

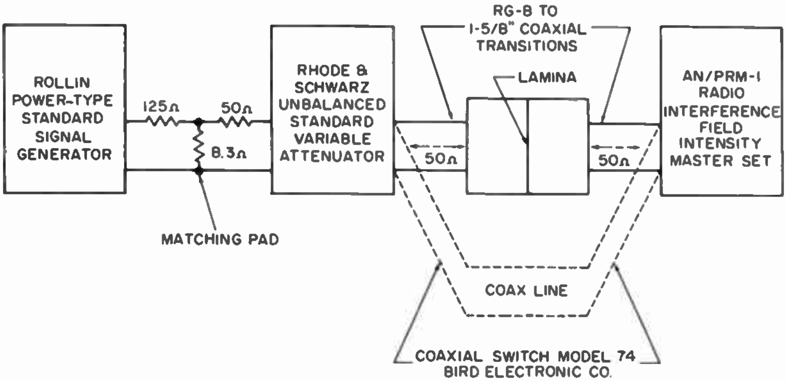


Fig. 8-18. Setup for measuring shielding effectiveness with the coaxial testing device.

Fig. 8-18 illustrates the method of using the coaxial testing device. It is constructed of standard 1⅝-inch coaxial guide with a 50-ohm characteristic impedance. Since the measurements are most easily interpreted when the device is fed by a 50-ohm source and terminated in a 50-ohm load, the device is isolated from the signal generator by a 50-ohm T-pad, and an impedance-matching network is used to match the output of the line to the field-intensity meter.

The construction of the device component that holds the sample under test is shown in Fig. 8-19. The threaded collars and stud are made of insulating material to circumvent the problem of contact resistance. While the contact resistance in the desired current paths is still present, the voltage drop across it does not appear across the voltmeter, so that the contact resistance does not influence the measurement. The use of an insulated stud and collar removes any undesired cur-

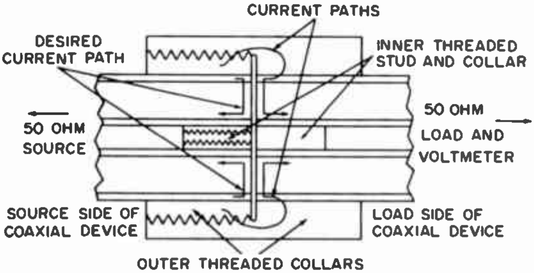
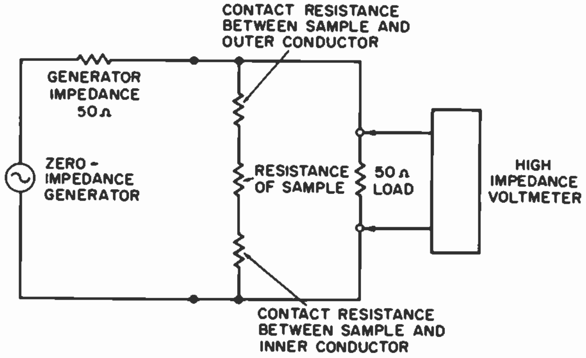


Fig. 8-19. Construction of the sample-receiving portion of a coaxial device.

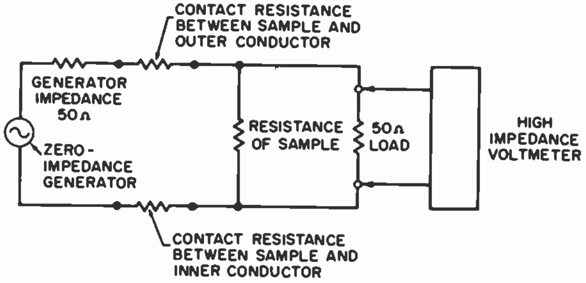
rent paths which might pass through the contact resistance between a lamina and load side of the line, were a conductor used instead of an insulator. The collar is made of linen-impregnated plastic, and the stud of nylon.

A circuit representation of the device appears in Fig. 8-20. Because the contact resistance and sample resistance are very small, the generator drives a current through the sample, which is determined almost entirely by the internal impedance of the generator. Consequently, a voltage drop appears across the contact resistances and sample, and this drop causes a current to flow through the load. Its magnitude is determined almost entirely by the load resistance. The voltage drop across the load can then be measured with the voltmeter.

Since the contact resistance may be larger than the sample resistance, it represents a very serious source of error. Soldering the sample to the coaxial device can help reduce contact resistance, but presents problems during assembly of the device.



WITH BRASS COLLARS AND STUD



WITH INSULATING COLLARS AND STUD

Fig. 8-20. Circuit equivalents for a coaxial device.

The set-up shown in Fig. 8-18 is used to take the data, which are plotted in Fig. 8-21 for a lamina thickness of 2.5 mils. The shielding effectiveness is much higher than the sensitivity of the instrument to detect beyond 5 mc. On the same graph, the calculated shielding effectivenesses are also plotted.

The experimental points are taken as follows:

1. With 20-db attenuation in the variable attenuator for isolation, a reading is taken on the field-intensity meter when the signal passes through the coaxial testing device.
2. Sufficient additional attenuation is inserted into the variable attenuator until the same indication as in Step 1 is observed on the field-intensity meter when the signal is fed directly to it by two coaxial switches (dotted lines in Fig. 8-21). The increase in db attenuation introduced by the variable attenuator is the shielding effectiveness of the lamina.

The experimental curve does not follow the calculated curve for shielding effectiveness, probably because of the generation of higher modes in the lamina. These modes, when generated at the surface of the lamina, are attenuated—especially at those frequencies where the lamina thickness, *d*, becomes an appreciable portion of the wavelength, *a*, and thus introduces additional loss. The higher modes are generated because the lamina is non-uniform, has surface irregularities, and the wavelength of the electromagnetic waves in it are quite small.

Fig. 8-22 shows the shielding effectiveness of high-*mu* metal 3.5 mils thick. The sensitivity of the instruments limits the

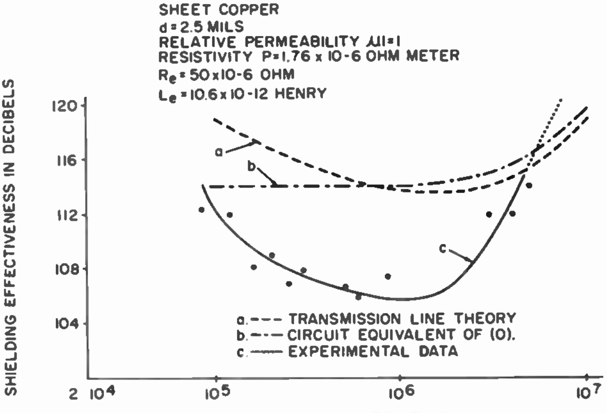


Fig. 8-21. Shielding effectiveness of sheet copper.

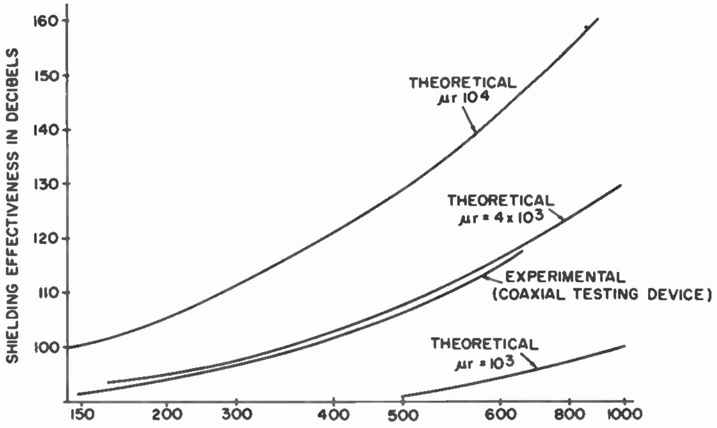


Fig. 8-22. Shielding effectiveness of high-mu metal.

measurement range to 650 kc. Figs. 8-23 through 8-26 show the shielding effectivenesses of aluminum 5 mils thick, 8-mil-thick stainless steel and 5-mil-thick magnetic steel, and the copper screening (22 × 22 strands per inch, 15 mils in diameter) of one shielding enclosure manufacturer. The effectiveness at very low frequencies is due primarily to reflection and the perforations have no effect until the higher frequencies, where effectiveness decreases as the frequency increases.

High-Permeability Metallic Foils

High-permeability metallic foils can be positioned to intercept the interference field and protect sensitive elements from the effects. This technique makes it possible to accommodate a wider range of flux densities for a given thickness of high-permeability shielding material. Since it is usually impossible to predict the fields which will affect any given equip-

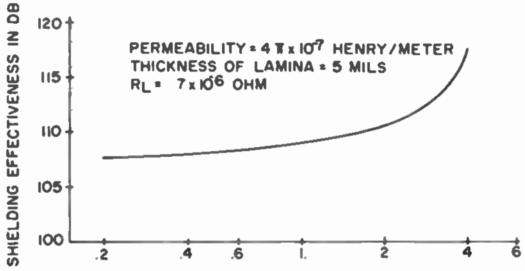


Fig. 8-23. Shielding effectiveness of aluminum.

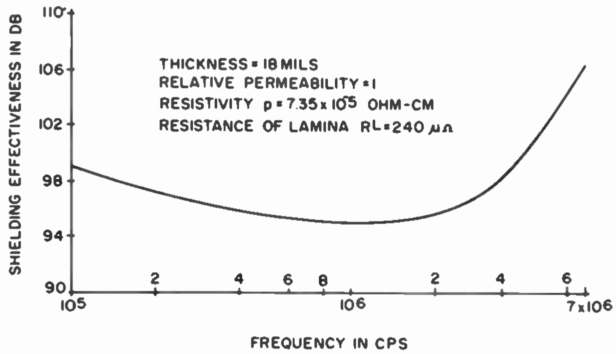


Fig. 8-24. Shielding effectiveness of stainless steel to plane waves.

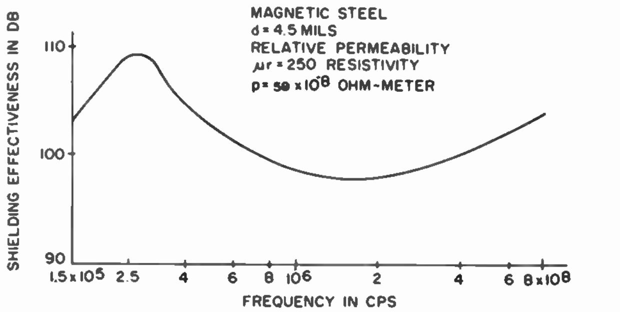


Fig. 8-25. Shielding effectiveness of magnetic steel to plane waves.

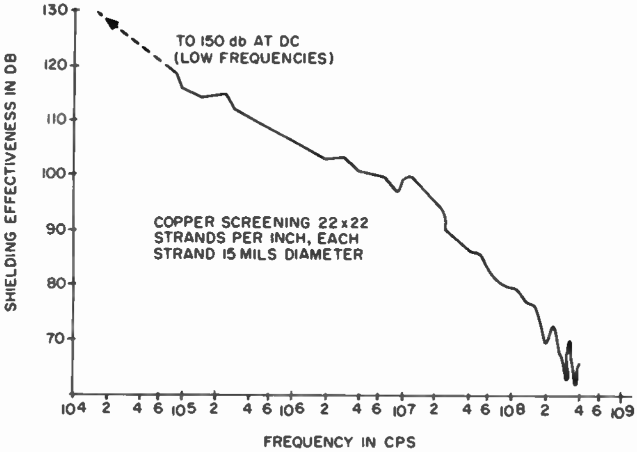


Fig. 8-26. Shielding effectiveness of single-layer copper screening to plane waves.

ment during operation, laminated foils are used to give added protection.

Laminated foils provide inexpensive and easily installed interference shields which can be placed around or between sensitive elements to localize the specific points where interference is causing trouble. Multiple layers of the foil can be used to determine the amount of shielding required to protect the sensitive area from interference.

A typical foil shielding-material application is the protection of electron tubes from RF-interference effects, such as a photomultiplier tube positioned within a group of other electronic components. If the tube is sensitive to magnetic fields it is obvious that the area surrounding the tube should be as free as possible from such fields to insure proper operation of the circuit. Proper shielding could be obtained by completely encompassing the tube with foil making certain the material overlaps at least one-half inch. The shield should be made as long as physical conditions permit, without shielding the photosensitive portion of the tube from the desired radiation. If possible it should extend beyond the over-all length of the tube structure. This foil cylinder can be placed directly over the glass envelope of the tube and taped together. Tests can be made with various numbers of layers to determine the required thickness to shield the tube from the interfering radiation. If a single layer proves inadequate, a second cylinder can be wrapped around the assembly with the lap seam positioned somewhere near 180° from the first seam. Again, the effectiveness should be evaluated and, if necessary, a third layer used.

Under critical shielding conditions, in which AC fields are involved, conductive shunts of low-permeability materials improve the shielding effectiveness. Materials have different permeabilities for alternate layers so that if the first layer has a relatively high permeability, the second layer will have a relatively low permeability. In the case of DC fields, the use of dielectric material between layers of high-permeability foil offers the simplest solution. Insulating material, or a nonmagnetic foil material such as aluminum or copper is placed between each layer of the shielding foil. In most cases involving fields of relatively low flux density, introducing a separating medium between shielding-foil laminas is not of any significant value.

Once the amount and type of interference shielding is determined an adequate shield can be fabricated from heavier stock, or if weight is a problem the foil shielding can be used permanently.

A common problem is shielding an input transformer to be used in a high-gain system. Such a transformer is generally enclosed in a metal housing to protect it physically and to provide mounting facilities. However, plastic cases which do not provide adequate protection against RF interference fields are sometimes used. If the system has objectionable effects from interference, foil shielding can be placed around the transformer. After the effect of a single layer has been determined, additional layers can be added, if necessary, in a manner similar to that used with tubes. Here, too, in instances where multilayer shields are found necessary (particularly in cases involving high-density flux fields), separating the layers with a dielectric material or a non-magnetic conductive foil is advantageous.

When it is desirable to enclose a field rather than keep a field out, the same procedure is employed as for the electron tube and transformer, but the sequence is reversed. In this case, the minimum field is external and the maximum field is internal, such as with a power transformer that must be enclosed to prevent interference radiation. The first layer around the transformer is the insulating material, which should be as thick as possible. This will space the layers of low-permeability foil as far as possible from the maximum leakage areas. If the field requires further reduction, a layer of high-permeability material should be used.

Planes of foil judiciously placed in positions of field concentration can in many instances serve as very effective shields. By experimentally positioning such pieces of foil where the fields are being generated or are causing difficulties, the effects can be readily evaluated by observation of equipment operation. By proper grounding of the foil, electrostatic shielding will be simultaneously accomplished.

Openings in Shields

A shield designed to completely enclose equipment or a component must have openings and other discontinuities for several purposes: to pass power, control, and output leads; allow access for adjustment maintenance and servicing; facilitate manufacture and assembly; and permit proper ventilation, drainage, and heat transfer. Of these, only ventilation (the circulation of air) and drainage of any condensed moisture require actual openings. All the other requirements can be satisfied with temporary, semipermanent, or permanent seals.

Leakage of electromagnetic energy through actual openings may be minimized by controlling either the size or shape of the holes. The amount of electromagnetic energy that can escape through a hole in a shield is roughly proportional to the size of the hole—provided that its dimensions are small compared with the wavelength of the electromagnetic energy. This means the leakage can be kept negligible merely by making the holes sufficiently small. When the only purpose of the hole is drainage of condensed moisture, a small number of holes no more than one-eighth inch in diameter is usually sufficient, and leakage through these holes is negligible except from extremely powerful interference sources such as ignition systems or radar modulators. For proper ventilation, larger openings are required; they must then be covered with fine-mesh copper screens, which must be soldered or welded along a continuous line around the edge of the opening. The type of mesh must be chosen in accordance with the principles explained earlier in this chapter.

Since, for effective shielding action, a mesh rarely has more than 50% open area and frequently less, the size of the openings must be correspondingly increased for effective ventilation. If the mesh must be easily removable, it should be attached with screws or bolts in sufficient number to insure a high-pressure contact along a continuous line completely around the edge. Here, as in other joints, maintenance constitutes the largest problem. The contact surface must be thoroughly cleaned each time the mesh is removed or replaced.

An alternative to reducing the size of the openings, either by making the holes themselves smaller or by covering them with metallic meshes to effectively make many small holes out of one big hole, is to shape the openings in such a manner that electromagnetic energy cannot escape through them. One way is to surround the openings with protruding sleeves. These, in effect, convert the openings into wave guides that pass without attenuation all frequencies above a certain frequency (determined by the geometry) and attenuate all frequencies below. A ¾-inch sleeve three inches long, for example, gives an attenuation of more than 100 db for all frequencies below 1000 mc. To be considered a wave guide, the sleeve length must equal at least three times the largest cross-sectional dimension (diameter if the sleeve is circular). Such construction, however, is practical only in a few special installations.

Joints

When it becomes necessary to join several parts of a complete shield together, the first consideration is to keep the number of joints to an absolute minimum. In practically all cases where joints are necessary, the shield should be constructed of no more than two parts having only one joint.

The most important requirement of a joint is that a continuous metal-to-metal contact be maintained. When the pressure is maintained by means of screws or bolts, a sufficient number must be used to insure high unit pressure, even at the points farthest from any screw or bolt. Lack of stiffness is an important factor in producing distortion of the mating surfaces, a condition which results in bulging and insufficient pressure for good electrical contact. Flange and cover-plate joints should be made circular whenever possible, because of the ease with which the surface can be machined either plane, grooved, or tapered. A retaining band can be used to maintain high unit pressure all around the joint.

A modification of the taper or wedge cover-plate design is shown in Fig. 8-27. Here, the shape of the mating members ensures positive contact along two continuous lines. For inner shielding materials, where screws cannot be used because the members are not stiff enough to maintain high pressure between screws, the "paint-can" cover shown in Fig. 8-28 gives good results. It can be used only for shields that need not be designed for strength and rigidity.

Failure of the flange and cover-plate configurations to provide continuous line contact necessitates the use of various types of conductive gaskets, as shown in Fig. 8-29. This type of material, usually known as "electronic weatherstripping," consists of a core covered with a foil or mesh; it is useful

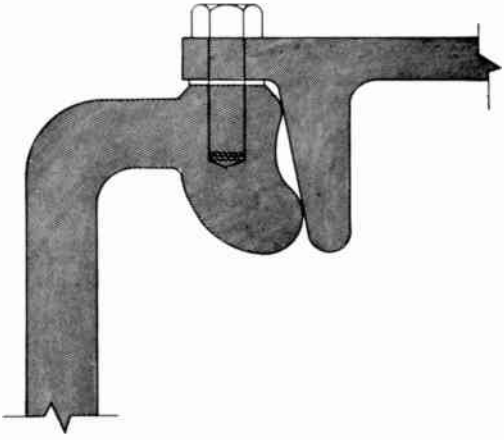


Fig. 8-27. Tapered cover plate design.

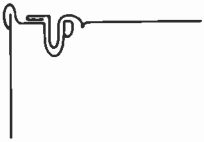


Fig. 8-28. Paint-can cover plate.

where a large joint is to be made and insufficient pressure is available for sealing.

In choosing the material for a conductive gasket, the electrical conductivity of the material is only one of many factors to be considered. High malleability and compressibility are also desirable. Such properties allow the gasket to conform to the mating surfaces, thereby allowing a greater contact area and a tighter joint under less pressure. For this reason, lead is satisfactory as a gasket material in spite of its relatively low electrical conductivity. Lead is also resistant to corrosion, another important property in gasket material.

Fig. 8-29 illustrates the use of a lead gasket in a flange joint. Here it is important that the gasket be located inside the flange bolts, to prevent leakage through the bolt holes. It is also important to have enough bolts to provide adequate pressure on the joint, to maintain line contact of the mating metals and to provide a low-impedance path at their interface. An insufficient number of bolts may cause the flange to warp under pressure. Suitable means should be provided for maintaining a constant pressure under operating conditions, should thermal changes or vibration be involved.

Just as in bonding, the matter of cleanliness is perhaps the most important factor in a good joint. The great difficulties in maintaining a joint electrically clean necessitate a continued search for joints that will maintain their electrical properties unchanged with time and repeated use. Improper

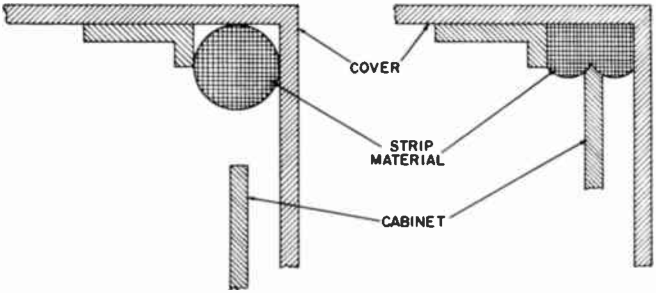


Fig. 8-29. Application of a round conductive shielding gasket.

or insufficient maintenance of shielding joints is one of the largest single causes of RF interference. Many times, the cleaning of a mating surface—or an additional turn of a screw that seems tight but is not—is all that is required to eliminate a major source of interference.

Even permanent joints, such as those which have been soldered, may fail in their purpose. Corroded surfaces are difficult to solder, and soldering may result in corrosion unless resin flux is used. The other three types of popular fluxes—the chloride, organic acid (waxes), and organic base types—are all corrosive, differing in their rate of attack rather than in the end effect. Resin, on the other hand, is not corrosive. For this reason, electrical joints between small, clean metal parts should always be made with resin flux, which is usually applied as a core within the solder wire.

Even a good soldered joint is likely to exhibit appreciable contact resistance. Grade-A solder has a conductivity of about 12.2%. Thus, an ideal soldered joint is never as good a conductor as a brazed or welded joint.

SHIELDED ENCLOSURE EFFECTIVENESS

Every major electronics laboratory has one or more shielded enclosures to provide an area as free as possible from undesired external magnetic fields. Conversely, these enclosures may also be used to confine radiation to a specified zone so that the outside of the enclosure will be free from interference. The shielded enclosure must reflect and attenuate fields which impinge upon its walls, either from the outside or the inside, over a wide frequency range. Plane-wave impedance fields and low-frequency fields with impedances varying from several hundredths of an ohm to several megohms may be encountered.

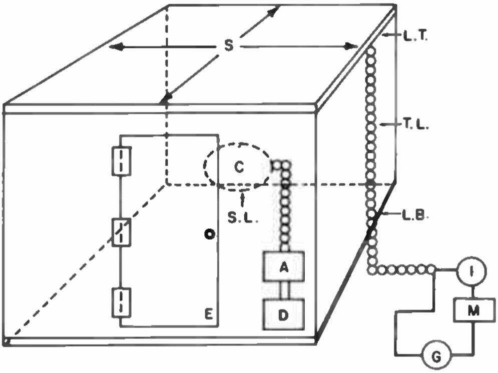
Tests are usually performed at three frequencies to determine the behavior of an enclosure designed to function from 14 kc to 10 gc. These tests are made at 15 kc, the lowest natural resonant frequency for the enclosure; at 9 gc; and between these two frequencies.

At low frequencies shielding against low-impedance fields is much more difficult than against other types of fields; consequently, a test using such fields is necessary. Enclosures exhibit resonances which affect shielding performance, and a test in this frequency range is necessary. In the VHF region, shielded enclosures do not perform as they do at lower frequencies. Therefore, in order to determine their effectiveness in the VHF range, tests are necessary.

Since the presence of low-impedance fields is quite common at low frequencies, the shielding effectiveness of an enclosure should be measured against low-impedance magnetic fields. These fields can be easily produced by current loops whose dimensions are small compared with the wavelength.

Low-Impedance Fields

One method used to produce low-impedance magnetic fields for testing shielded enclosures employs a large rectangular loop completely surrounding the enclosure. The loop-to-enclosure wall separation is two inches. When a moderate current flows in the turns of the loop, it produces a strong magnetic field which completely surrounds the shielded enclosure. This arrangement simplifies measurements on the over-all performance of the enclosure. The method may also include exciting a small loop inside and measuring the induced voltage in the larger outer loop (Fig. 8-30).



A—low noise narrow-bandpass amplifier (not required with AN/URM-6).
C—center of shielded enclosure.
D—Radio Interference Set AN/URM-6 or high impedance AC voltmeter such as Hewlett-Packard 400 D.
E—enclosure entrance.
G—low-impedance signal source capable of adequate output at test frequency, such as Hewlett-Packard 205 AG.
I—audio frequency ammeter satisfactory at 15 kilocycles or an AC voltmeter across a 1-ohm noninductive resistor.
LB—bottom loop.
LT—top loop.
(Both LB and LT 10 turns of No. 18 insulated wire horizontally oriented and circling entire enclosure.)
M—impedance matching transformer.
S—outer shielding layer.
SL—circular loop. Antenna AT-205/URM-6 in conjunction with AN/URM-6, or 10-turn 12-inch-diameter loop of No. 12 AWG enameled-copper insulated wire, placed in center of room midway between LT and LB.
TL—twisted leads.

Fig. 8-30. Measurement of shielding effectiveness to low-impedance fields.

The large rectangular loop consists of ten turns of No. 18 plastic-covered wire having a DC resistance of 2.6 ohms. Measurements of the loop input impedance are made with the loop placed horizontally midway down the screen-room wall. A typical impedance value is 25 + j1450 ohms.

To obtain a sufficiently large value of current in the loop so measurable fields will be induced inside the shielded enclosure, the loop inductance is tuned out, at 200 kc, using a 480-mmf capacitor. The inductance of the loop, when calculated from the impedance and capacitance measurements, is therefore 1.5 and 1.32 mh, respectively. However, no capacitance is needed between 12 to 20 kc, since the loop is self-resonant between these frequencies.

The large rectangular loop is used in conjunction with a circular 12-inch, ten-turn loop. A voltage is induced in the ten-turn loop at the center of the enclosure as the large loop is excited by current of the desired frequency. This voltage is compared with the theoretically expected voltage induced in the absence of the enclosure. Measurements are taken in the center and plane of the large outside loop. In addition, the shielding effectiveness is measured using two small coplanar loops at 15 kc and 200 mc. Signal generators such as the Hewlett-Packard Model 205AG and Rollin Model 20 Power-Type may be employed as the signal source. An RI/FI (radio interference/field intensity) meter, a Hewlett-Packard Model 400D voltmeter, or an equivalent instrument may be used as the detector, or measuring device.

Effect of leaky joints—A small loop is used for locating leaks in the shielding while the large loop is exciting the room from the outside. The search loop is carried around the periphery of the enclosure and at the same height as the rectangular loop. When this is done, the variation in pickup voltage is very pronounced near leaky joints in the walls or seams of the enclosure. Small defects such as separation of the conductors or a small hole in the screening are detectable with the probe not only along the wall at the same level as the outside loop, but also near the top and bottom of the enclosure as well.

Fig. 8-31 is a plan view showing the relative magnitude of the magnetic field at 12 kc inside the shielded enclosure as detected by the small search loop. The pronounced variation of field intensity near leaky joints is very evident. The illustration indicates that the joint near the hinge side of the door is leaking considerably; when this joint is tightened and the test repeated, the amount of leakage is reduced considerably as indicated in Fig. 8-32.

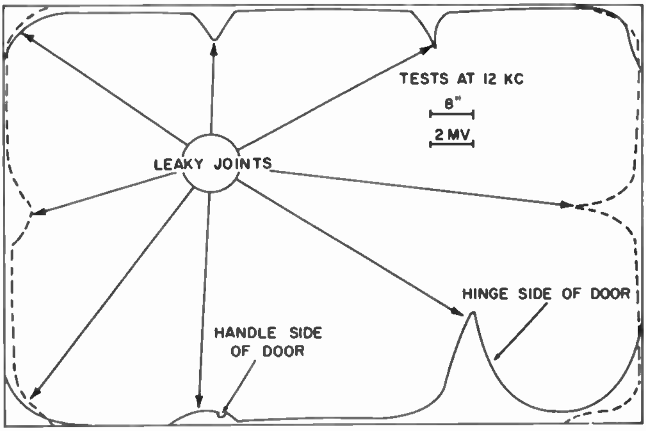


Fig. 8-31. Plan view of shielded enclosure showing effect of leaky joints.

Leaky joints parallel to the direction of the current through the large loop around the enclosure are not detectable by this test. Therefore, to detect all possible leaky joints in a rectangular enclosure, three sets of tests should be performed corresponding to the three possible orientations of the joints.

Midfrequency Tests

The presence of standing waves in a shielded enclosure at or near its resonant frequencies reduces the shielding effectiveness. The reason is that an impinging electromagnetic field

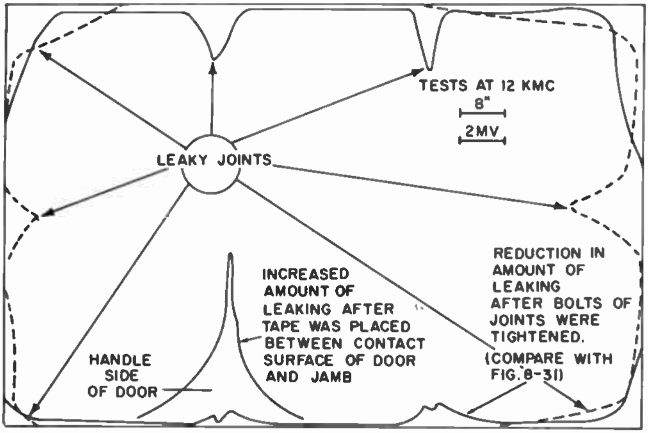


Fig. 8-32. Plan view of shielded enclosure showing effect after joints have been tightened.

can generate much larger fields inside the enclosure than would be possible in absence of resonance effects. Furthermore, the field intensity inside the enclosure can vary over wide limits because the Q is high when the shielded enclosure is considered a cavity. Consequently, the performance of any electrical equipment placed inside the enclosure, at points where the field intensity is high because of resonance, may be affected unfavorably.

The shielded enclosure also affects the impedance of the half-wave dipole antenna usually employed to measure its effectiveness at these frequencies. It makes the antenna appear more reactive when used inside the enclosure than when used outside.

The presence of standing waves and the change of antenna impedance make any shielding questionable at these (resonant) frequencies unless the enclosure response at such frequencies is known. Performance at the resonant frequencies of the enclosure cannot be predicted from the known enclosure behavior at either low or high frequencies. Therefore, a test should be established at or near the natural resonant frequencies of the enclosure. This test is required only at the lowest natural resonant frequency, however.

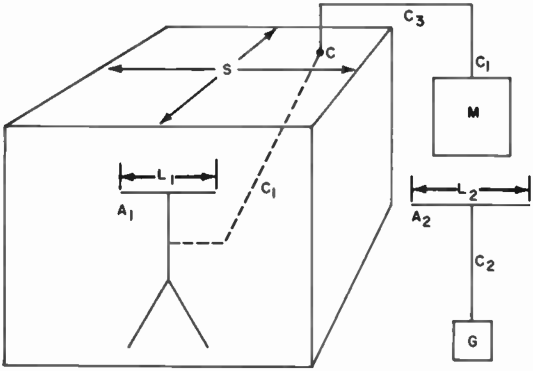
The shielding effectiveness of the enclosure at the midfrequencies is measured with the set-up shown in Fig. 8-33. Because of the high attenuation introduced by the shielded enclosure in the midfrequency region, a high-powered signal generator must be used. The generator feeds a half-wave dipole antenna (A2 of Fig. 8-33) through a 500-ohm doubly-shielded cable. Near the enclosure the antenna produces strong free-field waves of plane-wave impedance. Another dipole antenna, only one-quarter wave in length (A1 of Fig. 8-33), is placed inside the enclosure. Unlike a half-wave dipole, its impedance does not change appreciably as the frequency sweeps past resonance, or when the antenna is taken outside the enclosure.

The output of antenna A1 is brought outside the enclosure to an RI/FI intensity meter. This is done through a coaxial feedthrough connector located in the roof of the enclosure. In order to minimize undesired pickup and field distortion, cable C_3 is kept as short as possible. In addition, excessive leakage at the RI/FI intensity meter may necessitate the construction of a shielded case for this meter. Cable C_3 is also provided with a third shield which is grounded at each end.

If the antenna is repositioned within the enclosure, the pickup voltage will also be changed. Moreover, any metallic object inside or outside the enclosure may affect the measurement. Such objects will increase the resonant frequency when placed where the magnetic field is maximum, and will reduce the resonant frequency when placed where the electric field is maximum. This is due to the losses within the walls.

Microwave Frequencies

The electrical qualities of shielding materials change with frequency. The reflection and attenuation losses, and therefore the shielding effectiveness, depend on the electrical parameters. For this reason, a high-frequency shielded-enclosure performance test is necessary. Shielding effectiveness at microwave frequencies is greatly affected by the spacing between shields (in the case of a doubly shielded enclosure) and by the spacing and size of the perforations in any screening material. The spacing between shields can support standing waves whenever it is equal to an integral number of half wavelengths. Theoretically, this situation could bring about a 3-db decrease in shielding effectiveness below the value of



A_1—receiving short-dipole antenna (same as transmitting antenna, with $l_1 \leqq \lambda/B$).

A_2—transmitting antenna; Half-wave dipole AB-371/U placed on tripod CADV-10545, with $l_2 = \lambda/2$.

C—feedthrough connector.

C_1, C_2, C_3—connected shielded coaxial cables.

G—high power signal generator capable of adequate output at test frequency, such as Rollin Power-type Generator 30A or equivalent.

M—Radio Interference Field Intensity Meter AN/URM-47.

S—enclosure shielding layers.

Test frequency—lowest natural resonant frequency of the enclosure considered as a cavity. In the case of a rectangular parallelepiped, the frequency, in megacycles, is:

$$150\sqrt{\frac{1}{a^2}+\frac{1}{l^2}}$$

where,

a and l are the dimensions, in meters, of the edges forming the larger sidewall of the enclosure.

Fig. 8-33. Shielding effectiveness measurement at midfrequency.

a single-screen enclosure. Leaking at joints also has appreciably greater effect at microwave frequencies.

Tests are performed at about 9.375 gc. The source may consist of any high-power radiator, such as a radar system. Its output is directed, by means of a rectangular horn, onto the screening material being tested. Reflection-coefficient variation of the horn, with distance from a plane sheet of shielding material, is measured with a ratio meter (Fig. 8-34), at 9.375 gc.

The standard of shielding effectiveness for the enclosure is taken as the amount of increase required in db setting of the detector output attenuator (*D* of Fig. 8-34) to obtain the same level in the detector when the enclosure walls (S1 and S2) are removed. The strong field generated may penetrate the case of detector D, the attenuator, or transmission-line cables C. For this reason, they must be placed away from the path of the transmitting antenna and its reflections, as shown in Fig. 8-34. The distance between the receiving and transmitting antennas is fixed.

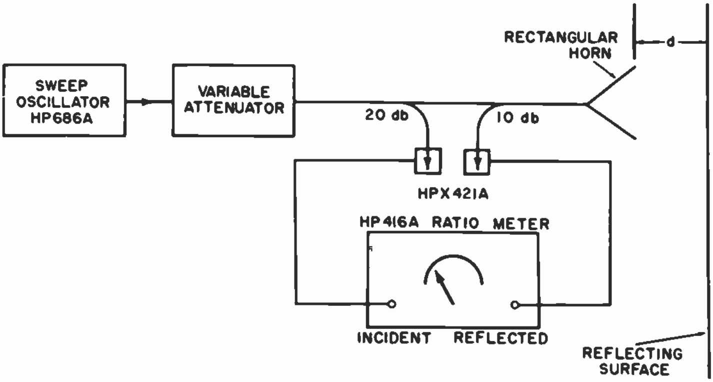
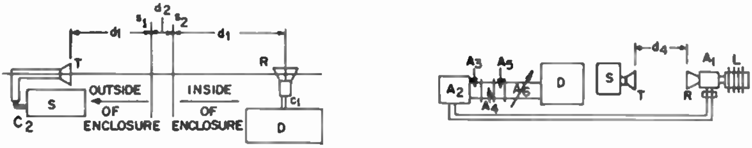


Fig. 8-34. Setup for measuring reflection coefficient of a horn antenna.

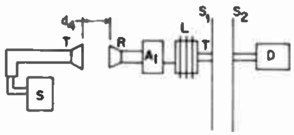
The transmitting antenna can be placed anywhere around the enclosure and in any orientation to the panel seams, door, etc., but must be perpendicular to the wall and away from any corner. At any one point, the shielding effectiveness will be maximum if the distance between shields of a multiple-shielding enclosure is equal to (2n-1)/4, and minimum if the distance is equal to n/2, where *n* is in wavelengths. These two distances represent small variations in the nominal one- or two-inch separations of the two shields. Measurements may be made at one point, and the two shielding layers, if non-rigid, may be pulled apart or pushed together slightly if necessary. Both maximum and minimum attenuation should be recorded.

A test should be made to assure that no leakage exists at *D*, *A*, or cables C1 and C2 (Fig. 8-35). A metallic plate is placed against *R* to completely cover the horn antenna. When this is done, the detector should show no leakage above the inherent background noise when cable C1 or C2 is disconnected and the end is capped. Nor should it show any indication as the transmitter is turned on and off.



(A) Measurement diagram.

(B) Equipment outside enclosure.



(C) Equipment inside enclosure.

A_1—directional coupler calibrated in db loss at the test frequency.
A_2—coax-to-waveguide coupler calibrated in db loss at test frequency.
A_3, A_4, A_5—constant waveguide attenuators calibrated in db loss at the test frequency.
A_6—variable waveguide attenuator calibrated in db loss at the test frequency.
c_1, c_2—transmission line cable, RG-9B/U.
D—AN/URM-42 with TN-131 tuning head, or detector of adequate sensitivity tuned to test frequency and used as a calibrated detector or as an equal-reference level indicator.
d_1—greater than 5 feet.
d_2—normally one or two inches.
d_3—distance from S_2 to center of enclosure.
d_4—$d_1 + d_2 + d_3$
f—test frequency in the X_s band (9 to 9.6 kmc).
L—dummy load; X912A may be used.
R—receiving antenna horn, such as AT-570/URM, or a standard-gain horn.
S—radar signal source.
s_1—outer shield.
s_2—inner shield.
T—transmitting X_s-band standard-gain horn antenna.
t_1—transmission line connector bonded to s_1 and s_2.

Fig. 8-35. Shielding effectiveness measurement at microwave frequencies.

If the detector shows no indication above background when the receiving antenna is inside the enclosure, the increase in attenuation needed to obtain receiver background when the receiving antenna is placed outside the enclosure indicates that the shielding provides at least the desired amount of attenuation. It could also indicate that the signal source is not strong enough, or that the detector is not sensitive enough for a full measurement.

The signal source may be a radar or any other X-band (3-cm) device of adequate output to obtain readings inside the enclosure (an enclosure will never completely block all radiation from such a strong source). The attenuators, couplers, and cables used are connected in series and must all be calibrated prior to the test.

Conduit

Flexible shielding conduit may be made of woven metal braid, strip metal formed into spiral bellows or some other kind of spiral that allows interlocking of adjacent strips, or a combination of the two.

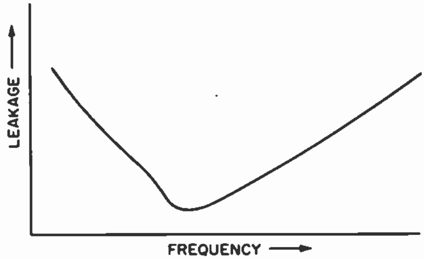


Fig. 8-36. Leakage from a typical flexible conduit.

Leakage of electromagnetic energy from flexible conduit is of two distinct types: the penetration through the metal, called "penetration leakage"; and the escape through breaks, joints, or openings, called "opening leakage." Penetration leakage decreases with frequency, whereas opening leakage does just the opposite. Both are present simultaneously, but the first is negligible at higher frequencies and the latter is usually negligible at lower frequencies. Total leakage, plotted as a function of frequency, usually follows the curve shown in Fig. 8-36. The slope at low frequencies is determined by the thickness of the metal, and the slope at high frequencies by the size and shape of the openings. The position of the minimum, which is characteristic of practically all flexible conduits, is determined by the design details.

When ignition systems contain resistor-suppressors, metal-braid woven over the ignition cable without internal metallic tubing provides adequate shielding. This produces a considerable savings in cost and weight, and eliminates the use of critical materials and tools.

The use of "pigtail" terminations (Fig. 8-37) was popular at one time, but should be avoided because the impedance is very high. Also, a considerable length of cable is left exposed, thus causing leakage of interference energy. Furthermore

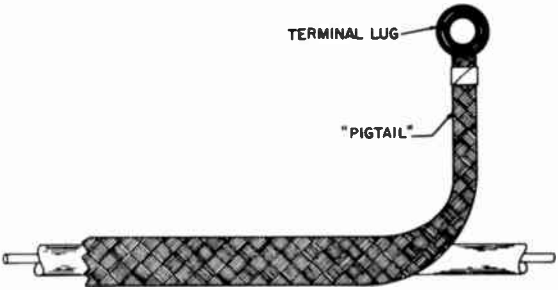


Fig. 8-37. Pigtail termination.

when pigtails are used, the last portion of braid covering the cable has a tendency to loosen and become frayed.

Cable clamps, when used, must be soldered to the braid and bonded to the structure with tooth-type lockwashers. The end of the braid must be soldered to prevent fraying. A drawing of such clamps, and the dimensions of the most common sizes, are shown in Fig. 8-38 and Table 8-1. A slot in the clamp

Table 8-1. Dimensions of shielding clamp.

Dimension	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
A	.037	.037	.037	.037	.020	.020	.020	.020
B	5/16	5/16	5/16	5/16	3/16	3/16	3/16	3/16
C	3/8	3/8	3/8	3/8	7/32	7/32	7/32	7/32
D	3/8	1/2	5/8	3/4	3/8	1/2	5/8	3/4
E	3/4	7/8	1	1-1/4	19/32	23/32	27/32	31/32
F	.201	.261	.323	.386	.201	.261	.323	.386

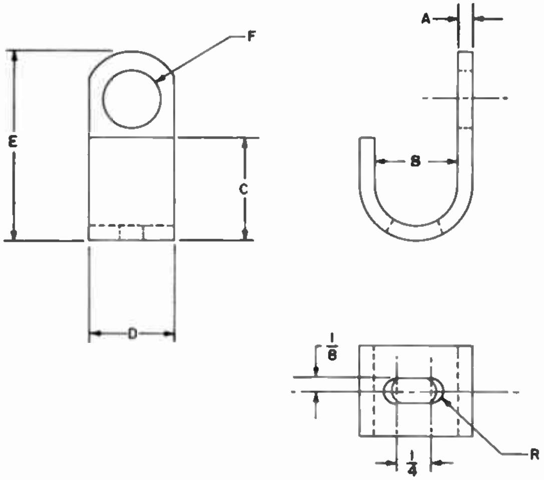


Fig. 8-38. Shielding clamp.

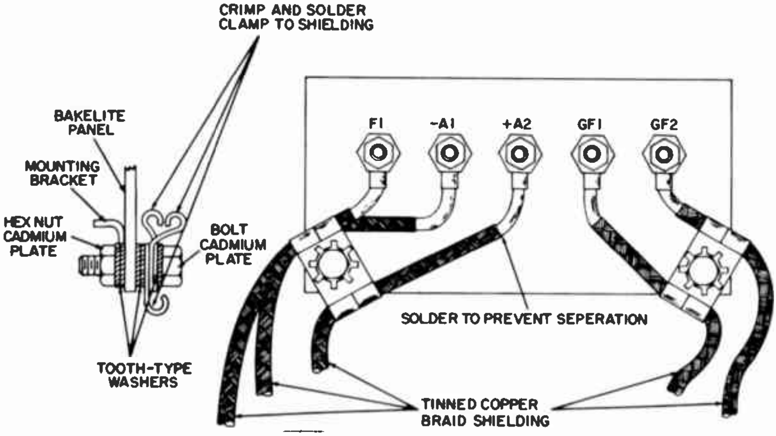


Fig. 8-39. Installation of a multiple clamp.

facilitates soldering. When several cables are close together, the multiple clamps shown in Fig. 8-39 may be used.

Where shielded cable is to be used with electrical or electronic equipment, similar wire braid should be used, terminated in threaded fittings as indicated in Fig. 8-40; the use of clamps is not recommended.

RESISTOR SUPPRESSORS

Resistor suppressors are series impedances inserted into a line to reduce interference currents. Since their impedance is resistive, it is independent of frequency. Consequently, the currents for which the system was designed are affected by them in the same manner as the interference currents. This restricts the use of resistor suppressors to those systems whose operation is not adversely affected by the insertion of additional resistance. By far the most important example of the effective use of resistor suppressors is the ignition system of internal-combustion engines.

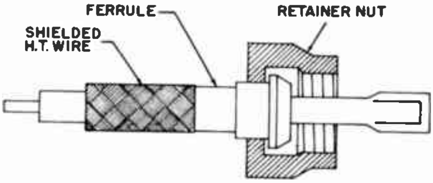


Fig. 8-40. Threaded fitting at the terminal of a cable shield.

Resistor suppressors, like all other suppression components, should be installed as close to the source of interference as possible. The use of components such as spark plugs, magnetos, and distributors in which the resistor suppressor has been made an integral part is recommended. A large number of examples of the use of integrally suppressed components are found in Chapter 10, which discusses ignition system components, including spark plugs, coils, alternators, etc.

VARIABLE-GAIN INTERFERENCE REDUCTION

In many instances, the performance of a receiver is seriously degraded by interfering signals from nearby adjacent-channel transmitters. Although these signals do not fall exactly at the center frequency of the receiver IF amplifier, their amplitude is sufficient to allow them to pass through the broad response of the IF amplifier. Once at the second detector, all frequency selectivity ceases.

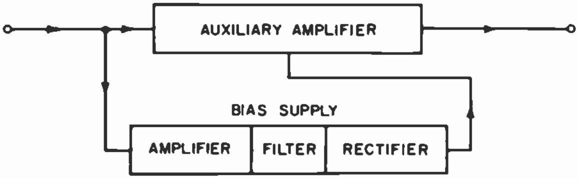


Fig. 8-41. Variable-gain interference-reduction block diagram.

A block diagram of a circuit which essentially behaves as a self-synchronizing blanker, to reduce the effects of such adjacent-channel interference, is shown in Fig. 8-41. The output of the final stage of the conventional receiver IF amplifier is fed to a bias-supply amplifier and then to a two-stage auxiliary amplifier whose gain is essentially unity. If the pulse center-frequency is the intermediate frequency, the incoming signal is transferred to the output of the auxiliary amplifier, where it is fed to the second-detector input of the conventional circuits of the receiver IF amplifier. The output of the bias-supply amplifier is connected to a band rejection filter which prevents the signal from reaching the bias-supply rectifier.

If the signal from the receiver IF stage is not at the intermediate frequency, it is passed through the bias-supply amplifier and filter to the bias-supply rectifier, where it is rectified and applied as a negative pulse to the auxiliary amplifier. This pulse cuts off or reduces the gain of the auxiliary amplifier for its duration.

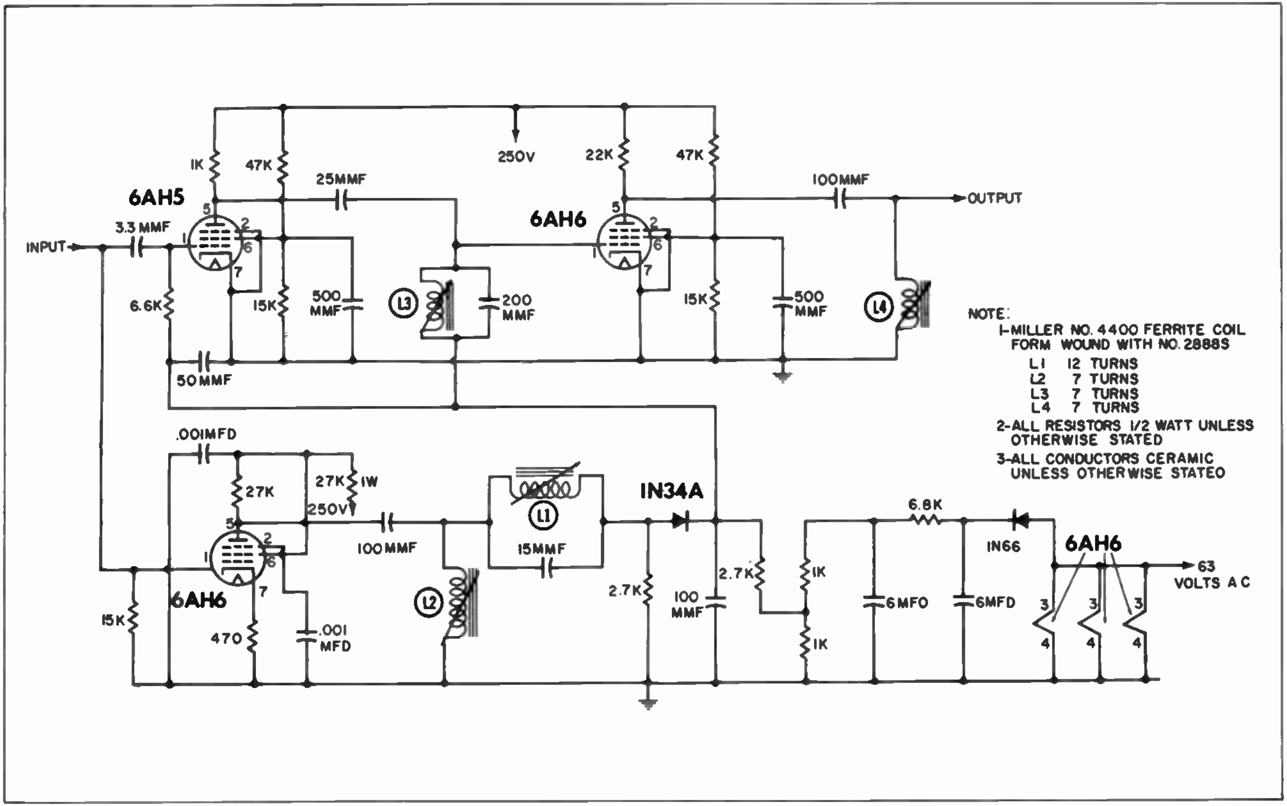


Fig. 8-42. Variable-gain interference-reduction circuit.

Circuit Theory

The circuit shown in Fig. 8-42 was designed to be installed in a radar receiver which already has adequate amplification; therefore the gain of the interference-reduction circuit is kept close to unity at the 30-mc operating frequency. This has been accomplished in several ways: the input coupling capacitor, being quite small, also serves to reduce the circuit input-capacity. In addition, low-valued plate-load resistors are used to reduce gain.

The bias supply is a single-stage amplifier which serves as both amplifier and limiter. The limiting action is desirable in order to have the bias-supply amplifier present a fairly constant signal level to the filter input. Satisfactory performance is obtained with input signals between 1 and 10 volts. Since the normal receiver IF amplifier is incapable of producing signals of amplitudes much larger than 10 volts, the upper limit presents no problem. If the input signal is below 1 volt, the interference-reduction device has little effect on the receiver performance as a whole. However, signals below this level should not produce serious interference difficulties anyway.

The filter consists of a tank circuit operating in conjunction with a fixed resistor. Its response is sufficiently broad to allow for the bandwidth of the usual target return pulses. In addition, the bandwidth is broad enough to accommodate any slight frequency variations present.

CHAPTER 9

Suppression in Rotating Machinery

Of all the sources of interference commonly encountered, rotating machinery represents one of the largest single groups. One or more motors or generators are installed in vehicles, cranes, power units, aircraft, boats, locomotives, and a wide variety of other equipment. For the purpose of this discussion, rotating machinery can be categorized into large DC motors and generators, alternators and synchronous motors, fractional-horsepower machines, and special-purpose machines.

COMMUTATORS AND BRUSHES

In all rotating machinery, there is relative motion between a set of conductors and a magnetic field. In generators, a conductor moves in a magnetic field in such a way as to cut across lines of magnetic flux, inducing a voltage in the conductor and causing a current to flow. Internally, both AC and DC generators produce an electrical voltage in basically the same manner. The method in which the electrical connections are made to the rotating member forms the difference between an AC and a DC machine; an AC generator has slip rings, and a DC generator has a commutator. In motors, electrical energy is supplied from an external source; the current-carrying conductor, located in a magnetic field, experiences a force that causes either it or the field to rotate. The same basic components are contained in both generators and motors.

The electrical contact to the rotor, which is necessary in all machines except certain induction motors, is made by brushes that ride on a slip ring or commutator. Since brushes are common to both AC and DC machines, they will be discussed here, and specific problems relating to brush-generated interference will be discussed later.

Commutation is essentially a switching action and, as such, is normally accompanied by interference-producing transients. Even with the best design, some interference is generated at the brushes and during commutation. To prevent interfering with communications, provision should be made in the original design of the motor or generator for the installation of capacitors at the brushes. Minimizing the lead length from the brush to the capacitor provides for more effective suppression.

The brushes and their leads are the most likely regions from which interference may be radiated or coupled into other circuits. Therefore, unless the entire machine is completely enclosed, the brushes, and their holders and leads, should be shielded as completely as possible without disturbing their normal functioning.

The friction between a brush and the slip ring or commutator causes both surfaces to wear, although the softer brush surface wears faster. The process of brush wear, which is gradual on a macroscopic scale, is actually very irregular and of a random nature on a microscopic scale. Fairly large carbon particles are torn loose and either ejected or burned. Hence the contact resistance, which depends both on the pressure and on actual contact area, is subject to sudden random variations of considerable magnitude. These variations result in steep transients and high-frequency harmonics, both of which cause RF interference. In extreme cases, the variations of pressure may be so great that the brush bounces completely off the metal, thus causing a true switching action. Brush-generated interference may be reduced by careful consideration of the following factors.

Brush Pressure

Generated interference decreases at all frequencies as the brush pressures increase (see Fig. 9-1). This speeds up the rate of wear, but the necessity of more frequent replacement should be considered a reasonable compromise for the sake of decreased interference generation.

Current Density

Generated interference decreases as the current density does, as shown in Fig. 9-2. As the current density increases, more heat is generated at the brush surface as it slides along the commutator or slip ring. This hastens the formation of a thick oxide film on the sliding metal surface. Rapid variations in the sliding-contact resistance, due to irregularities in the oxide film, cause high-frequency transients and RF interference.

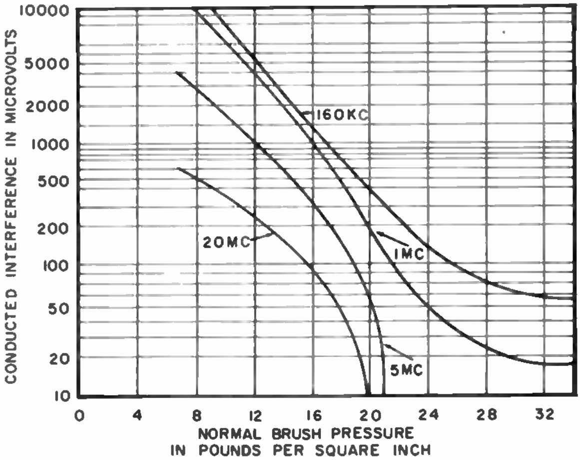


Fig. 9-1. Effect of brush pressure on interference generation at various frequencies.

Therefore, a somewhat larger brush-surface area should be provided than is demanded by consideration of the heat dissipation and losses due to mechanical friction. If the current density is too low, however, nonuniform grooves develop on the metal surface or commutator; and frequently the increased friction, due to the wider brush-surface area, sets the brushes

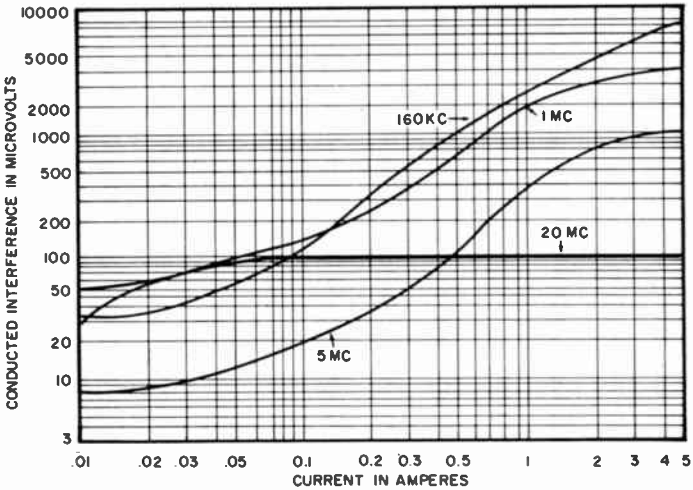


Fig. 9-2. Effect of brush current on generated interference at various frequencies.

into a noisy chatter. A good compromise requires a contact current density of 55 to 65 amps per square inch at full load for electrographitic carbon brushes, or 65 to 90 amps per square inch for metal-graphite brushes.

Brush Resistivity

Less interference is generated for brush materials of lower resistivities. Good performance is achieved by using an electrographitic carbon brush with 0.0015- to 0.0025-ohm specific resistance in machines being used at less than 50 volts. Low-resistance brushes are available with silver- copper- or cadmium-impregnated graphite. When used with a commutator, the brush should have a resistance that is in accordance with the requirements for good commutation; nevertheless, the material which has the lowest resistivity and still satisfies the other requirements of good functional performance is preferred. When the brush is used with slip rings, a wider choice of material is permitted since no switching action is involved. Using brushes of low resistance decreases the amount of interference generated considerably.

DC GENERATORS AND MOTORS

Of all rotating machinery, DC generators and motors are the two most serious offenders because they require commutators, which are severe sources of interference. In order to understand the interference-generating characteristics of a commutator, a brief discussion of the operation of a DC generator is required.

DC Generator

Fig. 9-3 illustrates an elementary DC generator. Loop coil ABCD is located in the magnetic field between the poles of an electromagnet. Its two ends are connected to two halves of a commutator, X and Y, which are insulated from each other. When the loop coil rotates in the magnetic field, it cuts the flux first in one direction and then in the other. This reverses the polarity of the output twice during each revolution and in this way provides an AC output. The commutator reverses the connections of the loop to the external circuit at the instant the polarity of the induced voltage in the loop coil reverses. The output of the simple single-loop DC generator is pulsating DC (Fig. 9-4). To increase the output and, at the same time, make it steady instead of pulsating, several coils are equally spaced around the armature and connected in series. Each

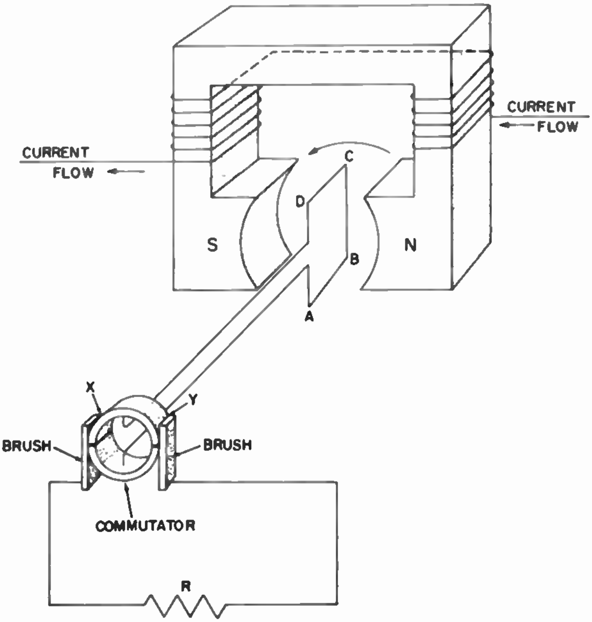


Fig. 9-3. Elementary DC generator.

coil is connected to a commutator segment. Fig. 9-5 illustrates a DC generator having several coils. Fig. 9-6 shows the effect of the additional coils on the output of the DC generator. Though considerably smoothed out, it still has some residual variation, called *ripple.* The frequency of this ripple voltage depends on the number of coils and the speed of rotation; the more coils per pole, the smaller the amplitude.

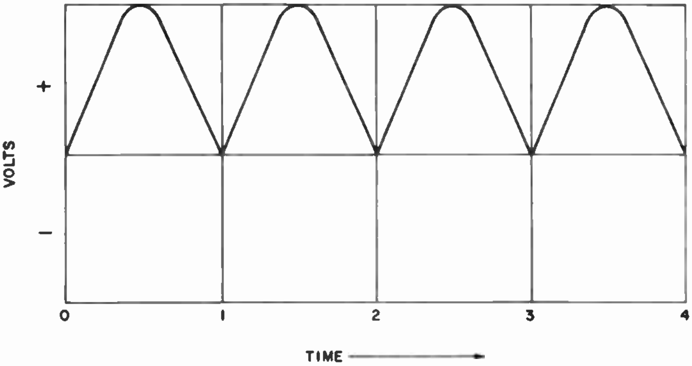


Fig. 9-4. Waveform of an elementary DC generator.

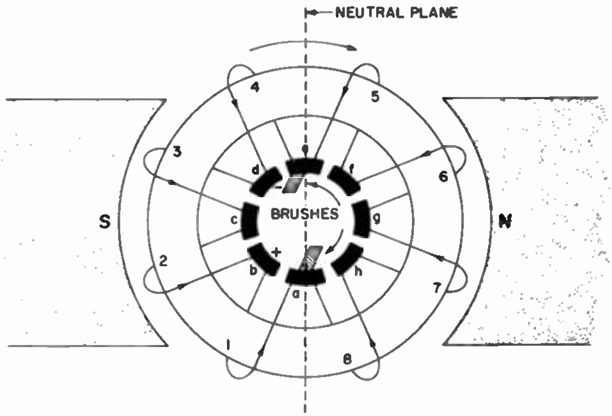


Fig. 9-5. DC generator with several coils.

Commutation—Commutation is essentially a switching action and, as such, is accompanied by interference-producing transients. It is produced by the brushes as they bear against the commutator. Hence, brush interference also contributes to the generation of interference in DC generators. In addition, the ripple voltages in the DC output can be a source of interference. Although their frequency is too low to interfere with communications, the harmonics can be troublesome.

Measures can be taken, during original design of a generator, to minimize the interference produced by the commutator action. One is to plate the commutator with chromium; another is to use laminated brushes.

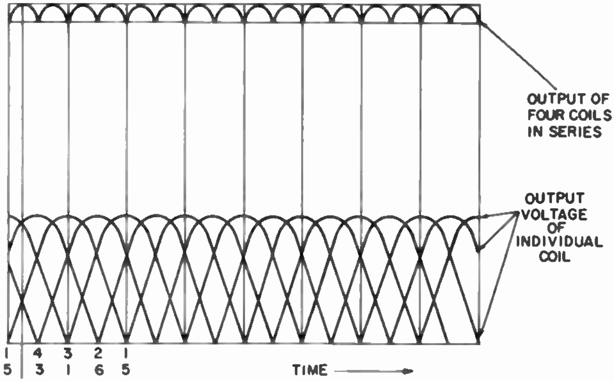


Fig. 9-6. Effect of coils in series on the output of a DC generator.

A copper commutator in contact with a carbon or graphite brush develops a layer of copper oxide, which mixes with carbon particles from brush wear after several hours' operation. This film introduces the same unidirectional electrical properties (polarity effects) encountered in a copper-oxide rectifier. The oxide layer has a nonlinear resistance which is higher at the brush acting as the cathode than at the brush acting as the anode. The cathode brush consequently passes current in discontinuous high-current-density surges. These surges often produce ten times as much interference as that from the anode brush. Much of this interference can be eliminated by plating the copper commutator with chromium to a thickness of about one mil; this will reduce the interference to that of a relatively quiet anode. In addition, the hard chromium surface prevents threading and grooving of the commutator, thus allowing greater choice in the selection of low-interference brushes. For many brush materials on chromium, the wear rate and sliding friction are the same as for copper.

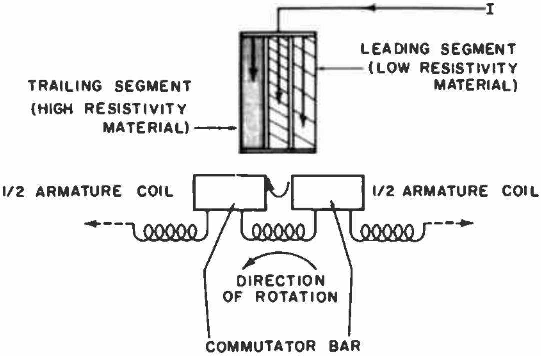


Fig. 9-7. Commutation of an armature coil by use of laminated brushes.

Laminated brushes consist of materials of different resistivity cemented to each other with a nonconducting glue which insulates adjacent brush segments. The ideal operation of laminated brushes is indicated in Fig. 9-7. By having successive brush segments of a lower resistance, the sharp current drop after the brush leaves the commutator segment is avoided. A more linear coil current reversal results, thereby considerably smoothing out the break transients (due to the switching action of the commutator).

Any design features that improve commutation will also reduce, but not eliminate, the generation of interference. To

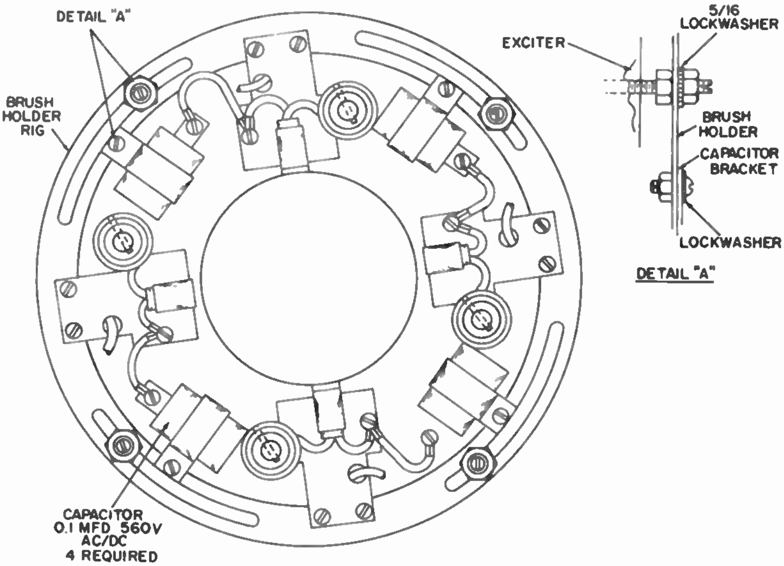


Fig. 9-8. Capacitors installed at exciter brushes in an alternator.

prevent this interference from disrupting radiocommunications, suppression measurements must be applied to the generator.

The most effective and economical method is to install capacitors at the brushes, in order to apply the suppression as close to the interference source as possible. The interference generated by the commutator and brushes will thus be bypassed to the generator housing. The lead from the brush to the capacitor should be as short as possible. Also, the capacitor should be adequately bonded to the generator housing, to provide a low-impedance path for the RF interference currents to ground. Fig. 9-8 illustrates a typical application of capacitors at the brushes in an exciter, which is essentially a DC generator.

Because of the combined interference-generating characteristics of the commutator and the brushes in a DC machine, an additional capacitor must be installed at the output (armature) terminal of the generator. The preferred installation is a feedthrough capacitor in the generator housing. The alternate installation is to mount a bypass capacitor externally, while maintaining a good electrical contact with the generator housing and minimizing the lead length between the terminal and capacitor. Fig. 9-9 illustrates the mounting of a bypass capacitor at the armature terminal. The capacitors will reduce the interference appearing externally on the armature and on the field terminals and wiring. However, over-all shielding is still necessary, to prevent the radiation of interference from within the generator. This shielding is accomplished by the generator housing.

Housing—Because of the necessity for ventilation, a fan is usually mounted on the front end of the housing, where it forces cooling air through the generator. This is the reason for the openings on the front and back ends of the generator. They should be screened with a copper mesh to hamper the radiation of interference.

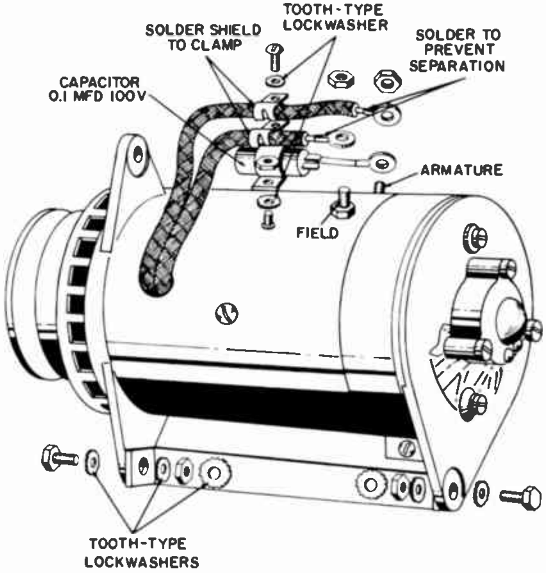


Fig. 9-9. A bypass capacitor mounted at the armature terminal of a DC generator.

No matter how perfectly a generator shield is designed, however, the shaft provides a path for interference since it must penetrate the shielding. This interference may be bypassed directly to the generator housing by grounding the shaft through a brush that rides on a special grounding slip ring or directly on the shaft, as shown in Fig. 9-10.

Another source of leakage from the shield is the inspection band. It is disadvantageously placed because of its proximity to the interference-generating brushes and commutator, but its function of permitting inspection of brushes and commutator prevents its being moved. To prevent leakage, the band should be as closely machined as possible and be wide enough to cover adequately the inspection opening, with sufficient overlap to assure good contact. It should be secured with a bolt and nut, rather than the less secure snap-ring mechanisms used in some designs. When the inspection band is removed, all paint and foreign matter should be removed from the contact surfaces on the band and generator before the band is replaced.

The final consideration is to ensure good contacts and low-impedance paths between the three sections of the generator, the two end plates, and the main housing. This is accomplished by good bonding and shielding practices.

Voltage Regulator—In order to maintain the output voltage constant in most DC generators, a voltage regulator is used to control the field excitation. This accounts for the armature terminal, which provides the output to the voltage regulator, and the field terminal, which receives the controlled voltage from the regulator, on most generators.

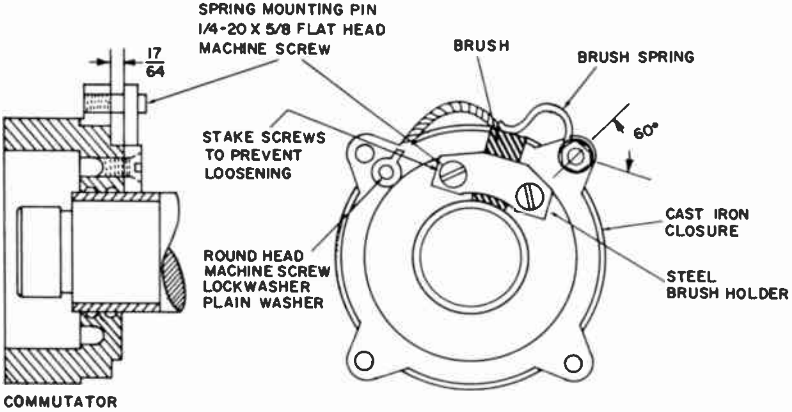


Fig. 9-10. Shaft bond for an alternator.

The voltage regulator should be installed as close to the generator as possible, to keep down the length of interconnecting wiring needed. The wiring can conduct interference from out of the generator regulator, and also serve as means for the radiation of interference into space. It should be shielded with tinned copper braid. The shorter the interconnecting wiring, the less shielding needed, of course.

Fig. 9-11 illustrates the installation of a voltage regulator on a generator. Capacitors (not shown) are inside the generator housing, at the brushes. The generator terminals are inside the voltage-regulator shield and thus are not interference sources. Leads between the regulator and generator are short enough not to require shielding, being entirely enclosed within the regulator shield. A capacitor is mounted within the voltage-regulator shield and is connected to the generator terminal of the regulator. It serves to bypass to ground any residual generator interference not suppressed by the capacitor at the brush, and also to bypass any interference generated by the regulator. The lead that goes from the regulator to the battery and carries the charging current to the battery is passed out of the regulator shield by a feedthrough capacitor. The action of the capacitor permits this lead, which is usually fairly long, to be unshielded. With the generator housing forming an effective shield, as discussed earlier, this is both an effective and an economical suppression system.

Over-all Suppression—Fig. 9-12 illustrates an alternate installation with an effective suppression system. The generator and plates are screened, and they maintain good contact with the main housing to form an effective shield. Grounding brushes, riding on the generator shaft, prevent interference from leaking out the shield via the shaft. A feedthrough capacitor in the generator housing bypasses to ground the interference generated by the brushes and commutator and conducted by the armature lead. The generator terminals are shielded. The regulator is mounted close to the generator. Both the field and armature leads are enclosed in tinned-copper braid shielding. A feedthrough capacitor in the voltage regu-

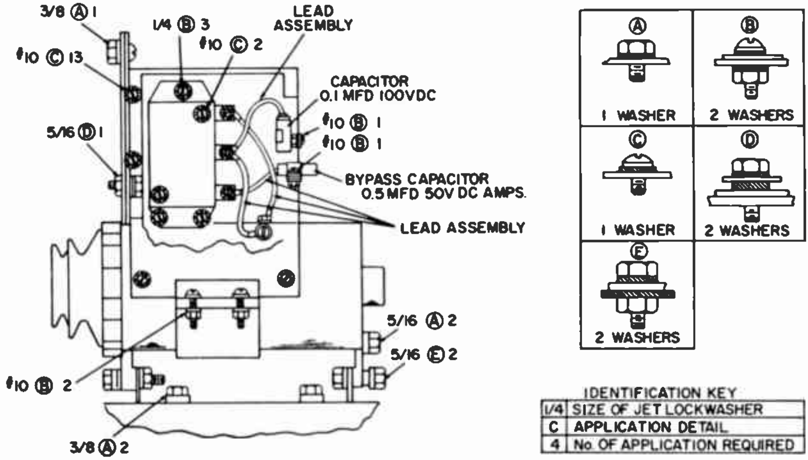
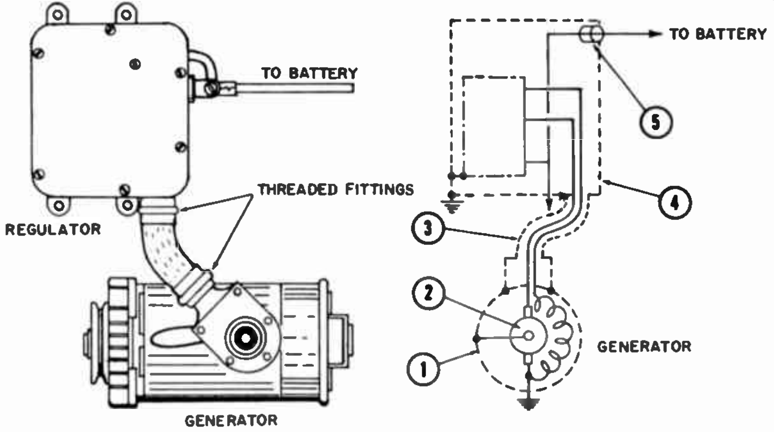


Fig. 9-11. Preferred installation of a voltage regulator on a generator.



1—generator frame and end castings form a shield that is grounded to the engine. The leads terminate in a housing that makes good electrical contact with the generator frame and the cable shield.

2—conductive brushes riding on the generator shaft, or on metal discs pressed on the shaft, at each end of the armature, grounded to the end castings.

3—flexible metallic shield enclosing the generator leads equipped with fittings that make good contact with the generator and regulator shielding box.

4—compartmented metal box enclosing the regulator and grounded through the mounting brackets to the structure of the machine or vehicle. A fitting makes good electrical contact with the cable shield.

5—2-microfarad coaxial capacitor, in series with the regulator output lead, mounted in the walls of a shielded compartment in the regulator shielding box and grounded to the walls of the shielding box.

Fig. 9-12. Suppression system for a battery-charging installation.

lator housing blocks any interference from the battery leads; thus no shielding is required.

Good bonding is essential in all effective suppression systems. The bypassing action of a capacitor depends on a low-impedance path to ground. Most DC generators are driven by and mounted directly on the engine; the latter permits the most effective bond for a component. Good bonding techniques should be observed—i.e., use of clean surfaces and plated tooth-type lockwashers.

The number of suppression measures needed depends on the original design of the generator. A well-designed generator, incorporating features to minimize interference generation, causes a minimum of trouble and needs a minimum of suppression. This is the most economical system of all and is standard for generator manufacture.

DC Motors

Suppression systems of DC generators are also applicable to DC motors. A generator will run as a motor and convert electrical energy into mechanical energy, provided the proper voltage is applied to the terminals. The use of DC motors should be avoided if possible, and another type of motor (such as an induction motor) substituted which generates less interference.

Commutator and brush interference and its suppression are generally the same for DC generators and motors. Any differences in suppression techniques stem from differences in installation and size of the unit.

The design considerations for minimizing the interference generated by the brushes and commutation action in DC generators also apply to DC motors. Capacitors can be installed at the brushes to bypass the generated interference to ground close to the source and thus provide an effective and economical means of suppression.

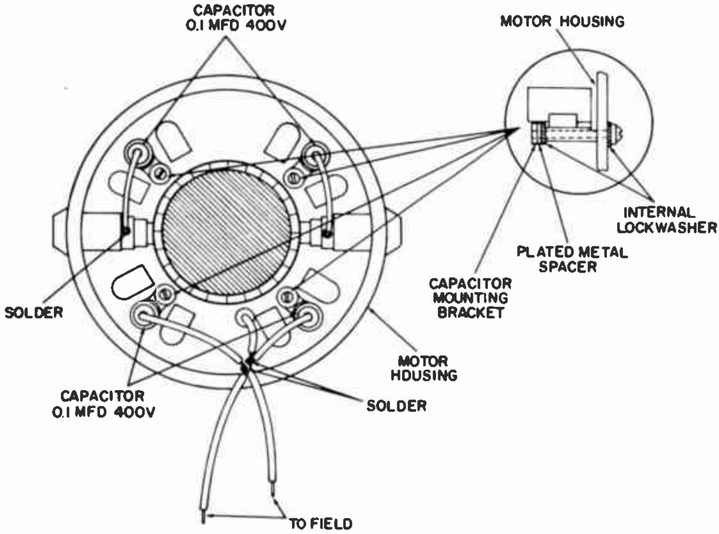
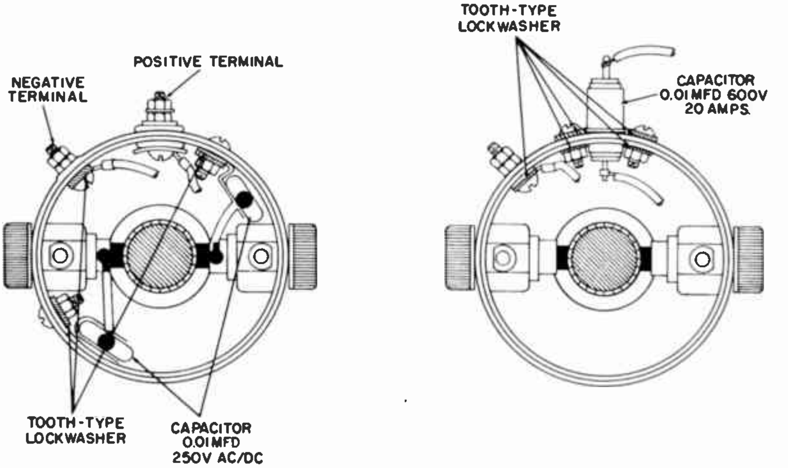


Fig. 9-13. Capacitor installed at the brushes and field leads in a DC motor.

Some DC motors include an adjustable speed control in which the field leads are connected to an externally mounted rheostat. This necessitates breaking the shield continuity, and provides a means for interference generated inside the motor to be conducted out of the housing. Capacitors, installed inside the motor housing, connected to these leads will bypass the interference to ground before it can escape. Fig. 9-13 illustrates a motor with four capacitors installed, one for each of the two brushes and two field leads.



(A) Preferred: Feedthrough capacitor mounted at the positive terminal.

(B) Alternate: Bypass capacitors mounted at the brushes.

Fig. 9-14. Capacitor installation in DC motor.

The preferred installation is to mount a feedthrough capacitor at the positive lead, as illustrated by Fig. 9-14A. Fig. 9-14B shows an alternate acceptable suppression system for the same motor, utilizing bypass capacitors at the brushes.

The principles of shielding are similar in both generators and motors. All ventilating louvres should be screened, and good contact should be achieved between the component parts of the motor housing. These are just two of the good shielding practices that should be followed.

Bonding necessitates more attention in a motor than in a generator because motors are usually not so advantageously placed. While a generator is usually mounted on its source of mechanical power, which is an effective ground, a motor is apt to be mounted anywhere, provided only that a sufficiently long power lead is available. For this reason, an effective return path must be provided without excessive bond-strap lengths. For motors that are mounted directly on engines, the return path is through the mounting. Provision should be made for good contact by using metal gaskets.

ALTERNATORS AND SYNCHRONOUS MOTORS

Alternators and synchronous motors are similar to DC generators and motors except that they supply or use AC and therefore have slip rings instead of commutators. Hence, commutator interference is absent in these machines (neglecting the exciter), and there remains only the interference from the brushes and from generation of harmonics.

Brush interference is lessened by the fact that most alternators and synchronous motors have a stationary armature and a rotating field; thus, heavy power currents need not be supplied to them. Only the much smaller field currents have to be supplied, through the brushes. Because commutation need not be considered in the selection of brushes, a much wider choice in brush pressure, size, and material is possible; and RF interference considerations can play an important part.

A well-designed machine generates a minimum amount of RF interference. However, even with the best design some harmonics are generated, and the need for external suppression remains.

Capacitors are usually the most effective suppression component and also the most economical. Fig. 9-15 illustrates the application of bypass capacitors at the slip-ring brushes of a 100-kw alternator. This serves to bypass interference due to brush action on the slip rings; it also removes the harmonic content. As in DC machines, interference is bypassed as close to the source as possible.

In addition to the interference generated by the brush action of the slip rings and the harmonics present in the sine-wave output of an alternator, the exciter is a prolific source. It is essentially a DC generator, and the discussion for DC generators and motors applies equally to it. Since both the exciter and the AC generator are installed in a single housing, shielding considerations are a combination problem, but the other suppression measures can be applied to the exciter as a separate unit. Plating of the commutator, use of proper brushes

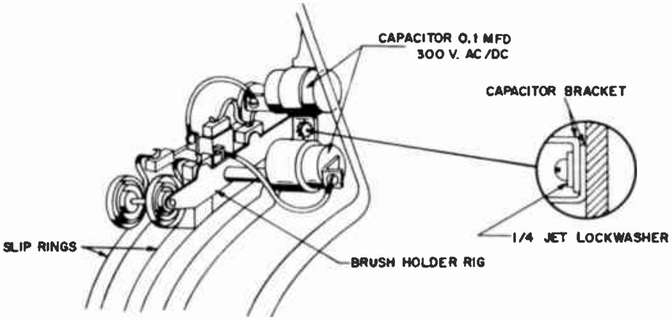


Fig. 9-15. Capacitor installed at the slip rings in an alternator.

and brush pressure, and use of bypass capacitors are applicable to the exciter. (Fig. 9-8 illustrates the application of capacitors at the exciter brushes.)

Although individually suppressed, the alternator and exciter will each generate some residual interference. It is suppressed by shielding and by the addition of bypass capacitors at the terminal outlets.

The original design of the alternator housing should incorporate the principles of good shielding. Low-impedance paths between sections of the housing, provision for adequate bonding, and screening of all ventilating slots should be carefully observed if the over-all suppression system is to be effective. As with DC generators, however, no matter how perfect the shield, the interference currents can escape via the alternator shaft, which penetrates the shield. This can be prevented by application of a shaft bond, a brush which rides on a special slip ring or directly on the shaft. (A shaft bond for a 300-kw alternator is illustrated in Fig. 9-10.)

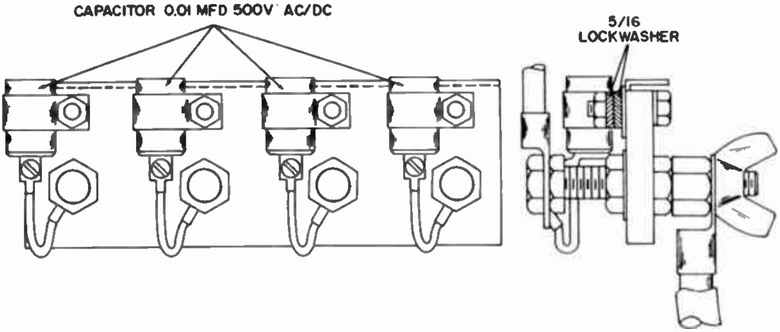


Fig. 9-16. Capacitors applied to the alternator terminal strip.

The alternator terminal outlets provide another means of leakage from the alternator. The remedy is to install bypass capacitors at the outlets. They are installed inside the terminal strip and connected to the terminal outlet just before the point where the terminal breaks the shield. This removes the interference from the lead at the last possible point, and thereby prevents interference from being coupled back into the lead and being radiated from the terminals or their wiring. Fig. 9-16 illustrates the installation of bypass capacitors at the alternator terminal strip. Another installation is to mount feedthrough capacitors through the terminal strip.

If the alternator includes a voltage regulator, its installation and that of the interconnecting wiring must be considered in the over-all suppression system. The voltage regulator controls the alternator output by regulating the DC voltage received from the exciter. Fig. 9-17 is a typical suppression system for a three-phase, four-wire alternator, using a voltage regulator to control the output.

The interference generated by the brush and commutator action in the exciter is bypassed by capacitors at the brushes. The output lead to the voltage regulator is shielded to prevent any residual interference from being radiated. The regulator also is shielded to prevent the radiation of interference generated within or conducted from the exciter. A feedthrough capacitor out of the regulator filters the lead to the field coils, permitting it to remain unshielded. The interference generated by the slip-ring brushes is bypassed to the alternator housing.

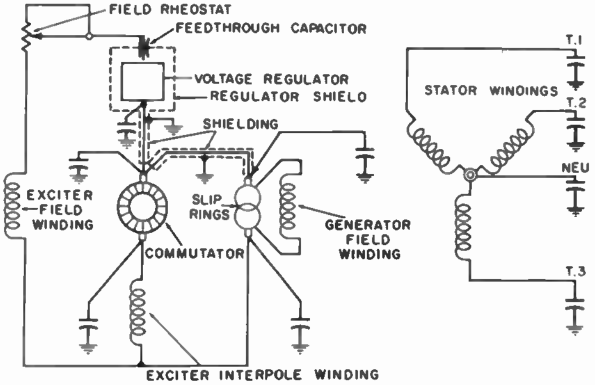


Fig. 9-17. Typical suppression system for an alternator, with a voltage regulator controlling the output.

Capacitors at the terminal outlets bypass any residual interference, to prevent it from appearing on the alternator output wiring.

The problems of interference suppression for an alternator also apply to synchronous motors. They have the same basic components as regulators, and will function as an alternator (and vice versa).

An induction motor should be used instead of a synchronous motor whenever possible, because of the lower interference generated. However, synchronous motors have certain performance characteristics that may make their use preferable in certain applications. If a synchronous motor must be used, the suppression techniques discussed for alternators are applicable.

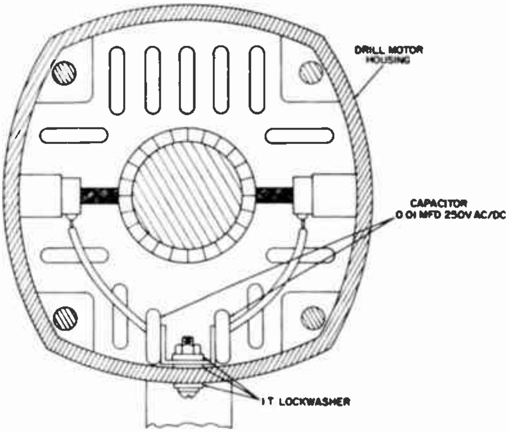


Fig. 9-18. Capacitors installed at the brushes in an AC-DC motor used in portable equipment.

PORTABLE FRACTIONAL-HORSEPOWER DEVICES

Portable fractional-horsepower devices include portable electric drills, utility and valve-seat grinders, portable electric saws, and valve-refacing machines. Power is furnished by high-speed, lightweight AC or AC-DC electric motors. The latter are unusually severe sources of interference because commutation is required for their operation.

As with DC motors, an effective, economical, method of suppressing commutator-brush interference is to install capacitors at the brushes. This is illustrated in Fig. 9-18 for a portable mill saw.

Size and shape prevent the installation of capacitors at the brushes of some AC-DC devices. It is more feasible and economical to mount the capacitors elsewhere on the machine. Installing capacitors at the line side of the switch bypasses interference to the unit housing at the last point of exit to the power lines. This prevents the interference from being coupled back into a lead and being conducted by the power lines. Fig. 9-19 illustrates the installation of feedthrough capacitors in the handle of a valve-seat grinder. Figs. 9-20 and 9-21 show two other possible installations, using both feedthrough and bypass capacitors. Both installations prevent interference from appearing in the power lines.

If the mechanical design of a device prevents installation of the capacitors on the line side of the switch, they can be installed on the motor side. Care must be taken, however, that there is no possibility of interference being coupled back into the leads before they leave the machine.

SPECIAL-PURPOSE MACHINES

Special-purpose rotating machinery includes a variety of equipment. The most important are rotary inverters, dynamotors, motor-generators, and generators for electric arc-welding systems. The function of conversion is common to most of these devices: AC is converted to DC or to higher-frequency AC; or DC is converted to a higher or lower DC voltage or to AC.

A rotary inverter converts DC to AC. Basically it is a DC motor with added taps on the armature winding, and with slip rings connected to the taps to provide the AC output. Interference is generated by both the AC and DC functions: commutator and brush action in the motor, and brush action and harmonics in the alternator.

Figs. 9-22 and 9-23 illustrate a suppression system applied to an inverter. Fig. 9-22 shows two feedthrough capacitors

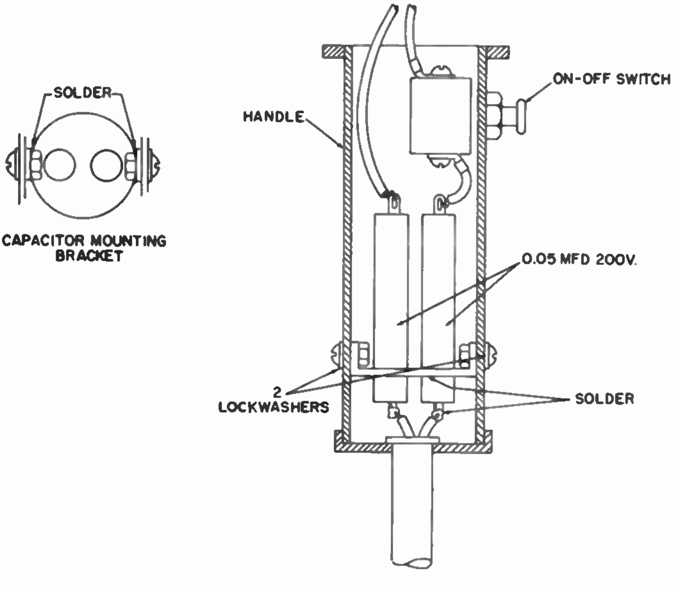


Fig. 9-19. Feedthrough capacitors installed in the handle of a portable valve-seat grinder.

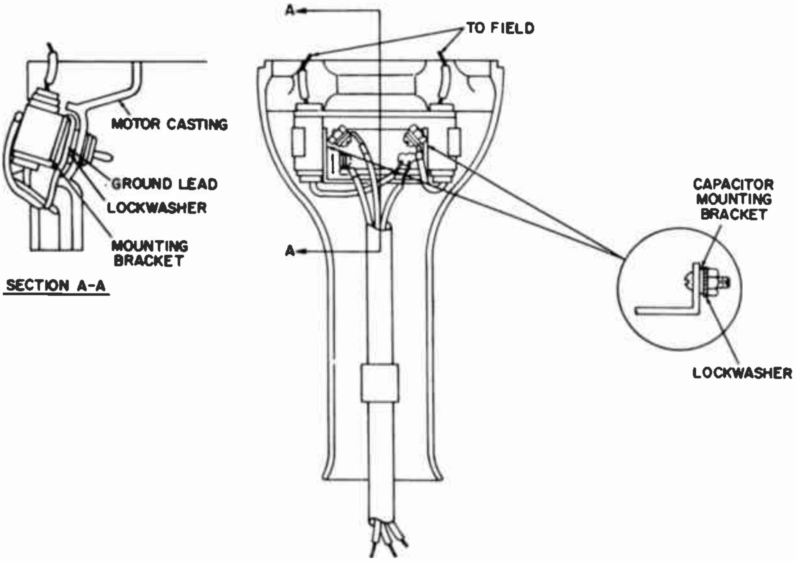


Fig. 9-20. Feedthrough capacitors installed in the handle of a portable electric grinder.

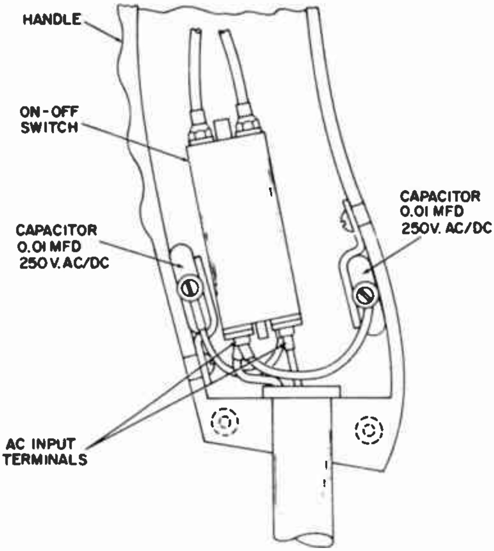


Fig. 9-21. Bypass capacitors installed in the handle of a portable impact tool.

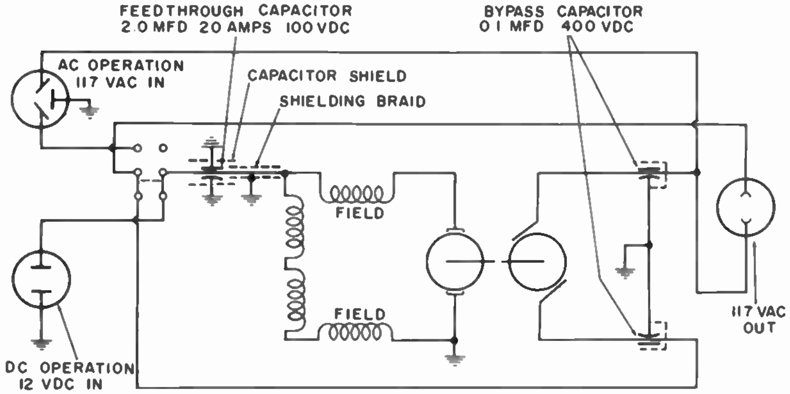


Fig. 9-22. Suppression circuit for a rotary inverter.

bypassing the interference from output leads of the alternator. The DC lead is shielded from the motor by a feedthrough capacitor. Fig. 9-23 shows the three feedthrough capacitors mounted in the inverter. In addition to the shielding and feedthrough capacitor on the DC line, a capacitor shield is installed to prevent radiation from the terminal on the "hot" side of the capacitor. This shield also provides a ground for

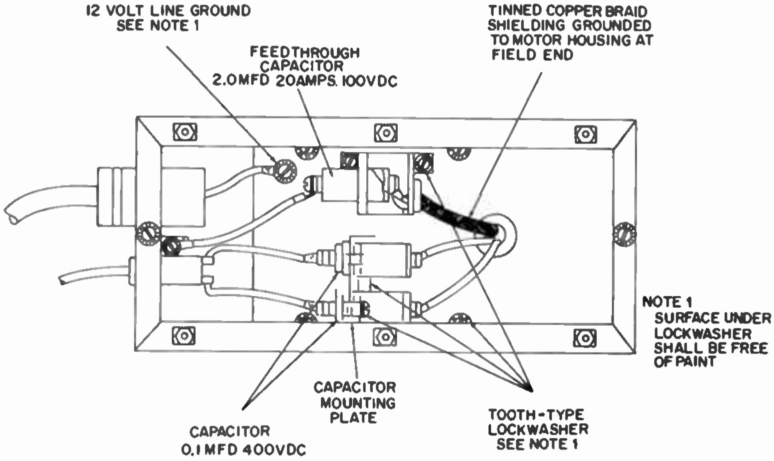


Fig. 9-23. Suppression system assembly.

the braid shielding. The AC output leads do not require shielding because the interference generated by the alternator is much less severe than that generated by the DC motor.

Th most efficient suppression system is one that is taken into consideration at the design stages of the machine. Bypass capacitors can be connected to the brushes in both the motor and alternator. The housing should adequately shield the unit with a feedthrough capacitor mounted through the shield for connection to the DC input lead. The AC leads may not require suppression, other than that provided by the capacitors at the brushes.

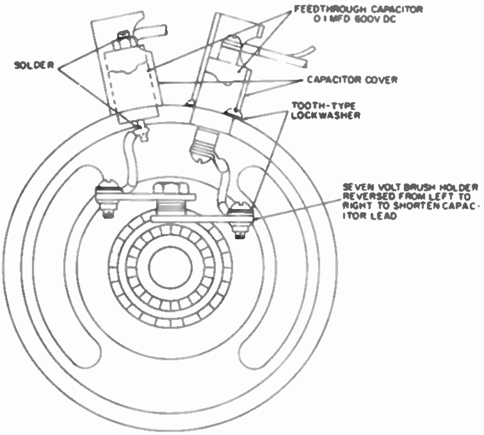


Fig. 9-24. Suppression system for a dynamotor.

DYNAMOTORS

A dynamotor is a combination DC motor and generator with a single magnetic field. It has an armature, which has two separate windings, and two separate commutators, one at each end of the armature. It transforms low-voltage DC to high-voltage DC, or vice versa.

The two commutators make this device a particularly prolific source of interference. The suppression techniques for DC generators and motors apply also to the dynamotor. Fig. 9-24 illustrates a dynamotor with feedthrough capacitors bypassing interference to the housing on both the input and output leads. Complete shielding of the dynamotor prevents interference from leaking through other paths.

There are various other types of special-purpose machines as well as variations of standard types. Motor generators are combinations of motors and generators having separate fields and armatures, but mounted on the same shaft and having common bases and bearings. Because these machines have combined functions in one housing, their interference is usually more severe than that from simple machines. Most types have at least one commutator. RF interference suppression of these combination units should be in accordance with the principles set forth earlier for simple machines. Each function (motor or generator) can be suppressed as a unit, but because of the increased circuitry, additional emphasis must be placed on proper lead routing. Otherwise, interference currents may be coupled from noisy to interference-free leads.

The use of AC commutator motors should be avoided whenever possible. Universal AC-DC motors fall into this category, as well as repulsion and series AC motors. Their advantage of high starting torque is offset by much worse interference than that from other AC motors.

Generators for electric arc-welding equipment are special only insofar as they are connected to a severe source of interference, the electric arc. The generator can be either AC or DC and is driven either by an AC or DC motor, or by an engine. The generator and driving source are suppressed in accordance with the discussion in this chapter. Nothing can be done to suppress the interference generated by the electric arc itself, except to use the equipment in the most propitious location possible. They should be placed in buildings with good shielding characteristics and away from communications equipment. The leads from the generator to the welding electrode can become very effective radiators and should be adequately shielded if there is any danger of interfering with nearby receivers.

Interference-generating characteristics should be considered along with performance characteristics when selecting a motor or generator for a particular application. In many cases, more than one type of device will meet performance requirements; the unit least likely to generate interference should be selected.

CHAPTER 10

Suppression in Ignition Systems

Ignition systems are designed to produce a synchronized electrical spark that ignites the compressed fuel inside the cylinders of an internal-combustion engine. There are two general types of ignition systems. The battery system includes a distributor, coil, and breaker points. A magneto system includes a magneto (within which all operating components are contained). Distribution wiring and spark plugs are common to both systems.

The ignition system is one of the worst offenders in the generation of RF interference because of the steep wave transients that ensue immediately after the firing of each spark plug.

SPARK PLUGS

Spark plugs produce the electric arc which ignites the fuel in the cylinder. This they do by using the power and voltage developed by other components of the ignition system. An analysis of this process in the battery system will illustrate the RF interference producing elements of the spark discharge.

When the distributor breaker points open, the secondary voltage rises, charging the capacitance (ignition-coil secondary self-capacitance as well as the distributed capacitance of the ignition cables) in the secondary circuit. Since this total capacitance is relatively small, the voltage rises rapidly to the value at which the spark-plug gap breaks down—whereupon the capacitance discharges, through the spark gap, to a voltage which will just maintain the spark across the gap. This constitutes the capacitive component of the spark discharge, which lasts only a few milliseconds at most and reaches a peak value of several thousand volts. This capacitive discharge is followed by an inductive component in which the energy stored magnetically in the ignition-coil secondary is dissipated through the gap. This inductive component becomes quite complex and unstable in a conventional ignition system since there is a discharge through the rotor gap in the distributor as well as through the plug gap. The two gaps break down alternately: The capacitance on the coil side of the distributor discharges through the rotor gap. This action charges the capacitance between the spark plug and distributor, and the capacitance is then discharged through the spark-plug electrodes. The time differential is a function of the relative capacitance on either side of the distributor gap. The instability and random spacing of the individual sparks in the inductive component are further aggravated by cylinder pressure and turbulence, and by minute variations in the distributor gap as the rotor passes the electrodes.

In each system, the spark is therefore snuffed out and restruck innumerable times while the energy in the inductive component is being dissipated through the gap. Each individual striking and snuffing out of the spark is of extremely short duration and of such frequency that the gap remains ionized between sparks. Consequently, a lower voltage is required to restrike the spark than to initiate it.

By inserting a 10,000-ohm resistor suppressor at the spark plug, the interference-producing inductive component can be smoothed out. In this way, the snuffing out and restriking of the sparks, are partially eliminated, and the energy stored in the inductance of the secondary is allowed to dissipate, uninterrupted, through the spark gap.

The difference between the effects of 1000 ohms and 10,000 ohms is appreciable. With the 10,000-ohm resistor at the spark plug, the inductive component appears as a continuous current flow through the gap; and as the resistance decreases, the spark again becomes intermittent.

While insertion of a resistor suppressor in series with the spark plug is a sound method for the suppression of extraneous oscillations, there is considerable apprehension as to the possibility of impairing the efficiency of the ignition system. This is due to the reduction in peak energy of the capacitive component of the spark discharge. However, tests have shown that resistor suppressors up to 150,000 ohms—many times greater than those used in suppression systems—have practically no effect on torque, fuel economy, or horsepower output. Fig. 10-1 shows the ratio of fuel consumption to brake horsepower for three spark plugs. The first is with no resistor suppressor,

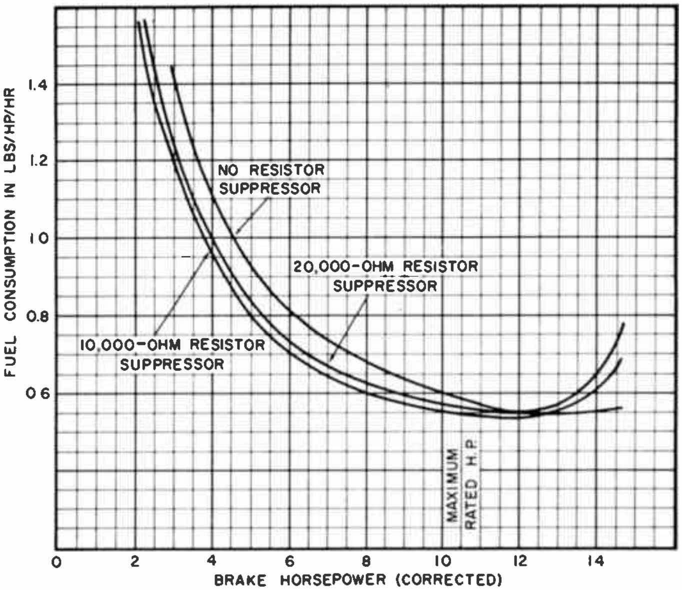


Fig. 10-1. Fuel-consumption characteristics of three spark plugs.

the second with a 10,000-ohm unit, and the third with a 20,000-ohm unit.

Another misconception concerning resistor suppressors is that they intensify the problems of cold starting. Results of carefully controlled tests have demonstrated that even below −30° F., suppressors are no deterrent to cold starting. In fact they sometimes permit almost instant starting, whereas an identical motor without suppressors might require several minutes of cranking.

Apparently the inductive component in the ignition spark discharge is more likely than the capacitive component to affect the combustion of an extremely cold mixture. With the inductive component appearing as a continuous current flow, the longer time at less total spark energy appears to be more effective in igniting cold gas than the higher heat energy in a more instantaneous spark.

An unexpected advantage found with suppressor-equipped spark plugs is the smaller gap growth. Tests on several engines running continuously at wide-open throttle reveal that the rate of gap growth in spark plugs with 10,000-ohm suppressors is only about one-half that experienced with standard plugs.

It is desirable for all vehicles as well as engine-generators and other engine-driven equipment to be furnished with inte-

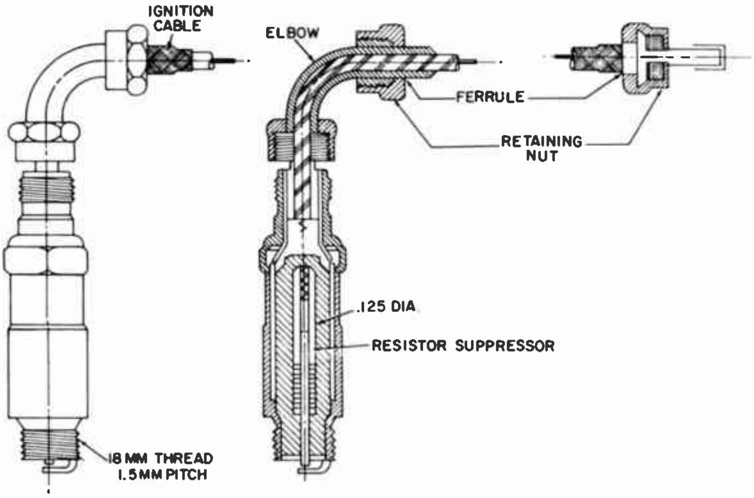


Fig. 10-2. Integrally suppressed spark plug.

grally suppressed spark plugs (Fig. 10-2), in which resistor-suppressor elements are built into the plugs. Integrally suppressed spark plugs are more effective suppressors because of the absence of any long lengths of exposed high-tension cable on the "hot" side of the suppressor, between it and the

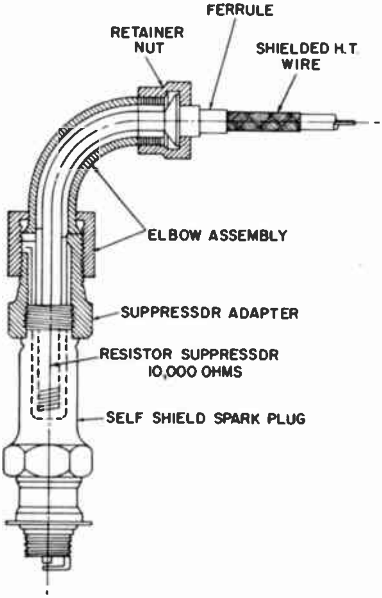


Fig. 10-3. External resistor suppressor installed at spark plug.

gap. This cable, required when external suppressors are used, may radiate considerable interference.

Where the spark plugs are not so suppressed, the application of an external resistor suppressor to a plug may solve a RF interference problem. Such an installation is shown in Fig. 10-3.

Despite the success of integrally suppressed spark plugs in reducing ignition interference from the inductive component of the spark discharge, they do not eliminate it entirely. The capacitive component is also responsible for steep wave transients in the secondary circuit, even though the peak energy is reduced. These two factors necessitate complete shielding of the high-tension circuit in the ignition system. Self-shielded plugs are preferred because there is less possibility of leakage of RF interference currents. The use of unshielded spark plugs should be avoided for all equipment when interference suppression is a necessity. Shielded spark plugs are readily available for almost all ignition systems.

DISTRIBUTORS

Distributors are essentially switching devices in which a rotor distributes the energy received from the coil to the various spark plugs. Fig. 10-4 illustrates this process.

The distributor has two actions, which can be severe sources of RF interference; switching causes a transient or variable current state, and arcing occurs between the rotor and the electrode during the switching.

Two 10,000-ohm resistor suppressors can be inserted, one in the lead from the coil, as close to the distributor input electrode as possible, and the other at the spark plug. This will increase the impedance of the high-tension circuit to more than 20,000 ohms. The net result is to reduce the magnitude of the current step and the steepness of the voltage step in the high-tension circuit so that considerably less RF interference is produced.

To repeat, the high-tension circuit, after installation of two resistor suppressors, will not contain a total resistance of more than 20,000 ohms. Again the question must be considered: "What is the effect of this additional resistance on the efficiency of the ignition system and subsequently on the engine?"

As before, exhaustive tests have shown that resistor suppressors up to 150,000 ohms, many times greater than any value used in the suppression system, have practically no effect on torque, fuel economy, or horsepower output. Likewise, the addition of the 10,000-ohm resistor suppressor at the distributor will have no adverse effect on cold-weather starting.

The advantage of employing resistor suppressors in the high-tension circuit is the adequate suppression of RF interference by using braided shielding on the ignition cables. To provide equal suppression without resistor suppressors requires the use of flexible conduit-type shielding on the ignition cables. Such shielding is costly and requires considerable quantities of copper, brass, and/or bronze. Moreover, greater care is required during production, and considerable maintenance.

The distributor finger or rotor, in rotating, passes close to but does not touch the electrodes. Since the high voltage obtained from the coil must jump the air gap between the rotor and electrode, the distributor can be compared to a spark transmitter. When the spark or arc occurs, considerable RF interference is generated.

Since arcing is part of the normal action of the distributor and not a product of malfunction or poor design, the RF interference generated cannot be eliminated. This interference can be radiated from the distributor, or it can be conducted out of the distributor by the ignition wiring and be radiated from it. Resistor suppressors will reduce the transients in the cabling sufficiently to make them a negligible factor; however, complete shielding of the distributor will still be necessary.

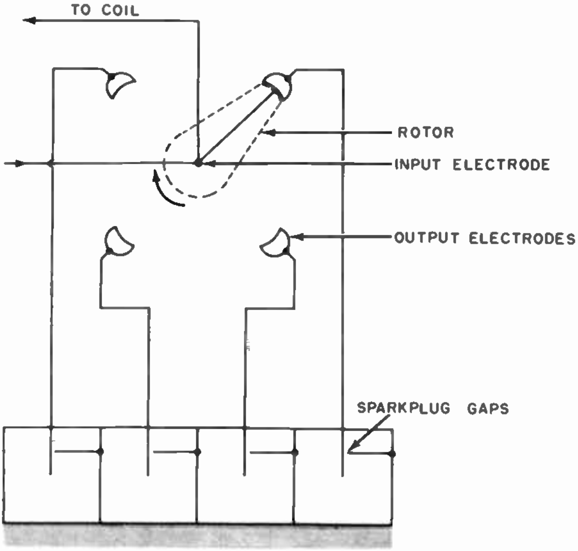


Fig. 10-4. Circuit of a distributor.

This shield must be designed so as to prevent any leakage through joints and seams.

Distributor shields are general-purpose, standardized types applicable to a variety of installations or shields designed for a specific ignition installation. General-purpose distributor shields should provide the utmost shielding efficiency to the most ignition installations.

Instead of enclosing the distributor in a separate shield, an ignitor or battery timer may be used. This is an integrally suppressed, self-shielded combination distributor and coil. Such an installation is more economical, minimizes the possibility of leakage, and requires less maintenance.

An integrally suppressed combination coil and distributor (ignitor or battery timer) should have the ignitor or distributor shield mounted on and bonded directly to the engine block. This provides the most effective bond for the shield and unit. The mounting ring and retaining nuts should be properly tightened, and tooth-type lockwashers should be used at the various mounting screws. Lead gaskets assure good electrical contact at all joints.

BREAKER POINTS

Although located in the distributor, the breaker-point assembly is part of the low-tension or primary circuit. This location is dictated by the necessity for synchronization between the breaker-point cam and distributor rotor, both of which are geared from the same drive in the engine.

The breaker points, or interrupter, break the primary circuit of the coil each time a cylinder must be fired (from 20 to 100 times a second, depending on the number of cylinders and the engine speed). Each time the contacts open, arcing is produced by the abrupt interruption of the current. The magnetic field built up around the coil then collapses, inducing a high voltage in the secondary winding of the coil. This sudden change initiates high-frequency transients, which are conducted along the low-tension wiring and can be radiated.

Different methods are necessary for interference suppression in the primary than were used in the secondary circuit. Resistor suppressors cannot be inserted in series with the breaker points because they would reduce the primary current below an operating value. The only solution is the installation of capacitors and shielding.

A capacitor is installed within the distributor housing, across the breaker points. It forms a low-frequency oscillating circuit with the primary winding of the coil and thus assists in extinguishing the arc at the contact. This will suppress extraneous oscillations and consequently reduce the interference; however, the inherent function of the breaker points makes it impossible to eliminate the transients entirely, since they are necessary to induce the high voltage in the secondary circuit. The size of this capacitance is limited because any increase will reduce the frequency of primary oscillation and consequently the induced voltage. Excessive capacitance across the points will also cause pitting of the contacts.

Shielding of the breaker point assembly is unnecessary because it is located within the distributor. Adequate shielding of the distributor suffices to suppress interference currents in the low-tension circuit.

The lead from the breaker-point assembly to the coil should be shielded and as short as possible to prevent radiation and possible coupling to other wiring. This includes not only the RF interference currents from the low-tension circuit, but also the currents from the high-tension circuit as well, because of the proximity of the two circuits at the distributor.

The ideal installation is to use a combination coil and distributor in a single housing. This minimizes the lead length between the breaker points and coil and completely encloses the lead.

The last consideration is the RF interference that can be conducted out of the ignitor. The high-tension wiring to the spark plugs has already been discussed; the low-tension wiring from the coil to the battery and ignition switch is described in the following.

COILS

The ignition coil links the primary and secondary circuit by taking the energy received from the battery and transform-

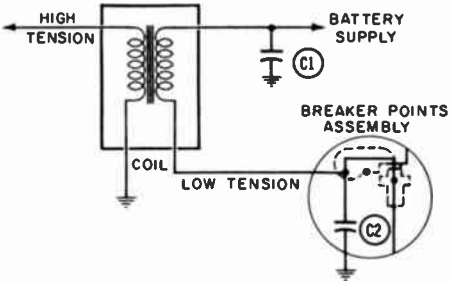


Fig. 10-5. Typical ignition primary circuit.

ing it to the high voltage necessary to fire the spark plugs (Fig. 10-5). The coil is conducting RF interference currents from both the primary and secondary circuits, and there is the possibility of radiation from the coil and its associated wiring.

Transients cannot be avoided in either the primary or secondary circuits. Resistor suppressors do dampen the transients in the secondary, but shielded leads are still necessary, to prevent radiation from the residual transients; no damping can be used in the primary circuit.

Two methods are required for suppressing RF interference from the coil: shielding to prevent radiation, and a capacitor to bypass high-frequency components to ground. Fig. 10-6 illustrates a shield with a capacitor installed.

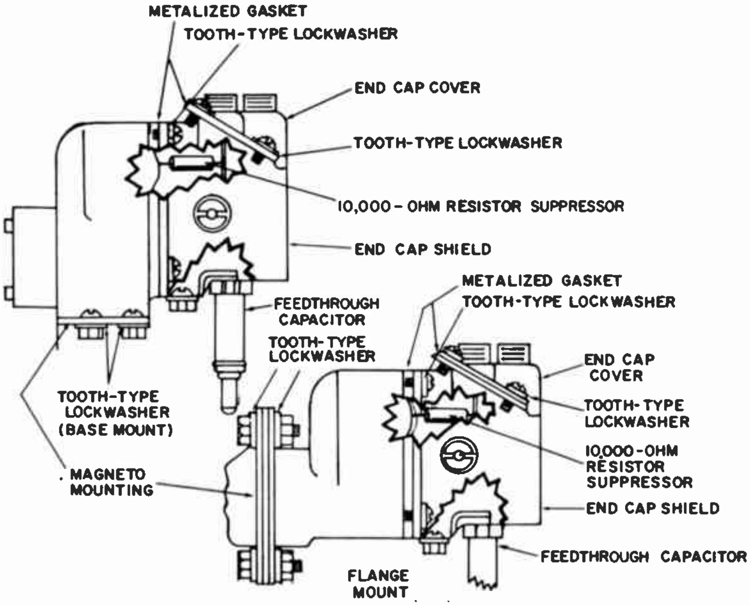


Fig. 10-6. Integrally suppressed shielded magneto with feedthrough capacitor to ignition-switch lead.

By shielding the coil, shielding of the entire secondary circuit is practically complete. The primary circuit is shielded except for the battery supply lead to the coil. This lead is necessarily long in most installations, and shielding it would be an expensive means of interference suppression. However, by inserting a capacitor on this lead, as close to the coil terminal as possible, the high-frequency components are bypassed to ground. A feedthrough capacitor is recommended. The one in Fig. 10-7 is installed externally; the lead from the coil terminal to the capacitor should be kept as short as possible. Fig. 10-8 shows a general-purpose coil shield with a feed-through capacitor installed in the battery supply lead.

The lead from the coil to the distributor is in the high-tension circuit and must be shielded. Installation of resistor suppressors at the distributor and spark plugs makes braided shielding adequate for this lead.

IGNITION HARNESSES

Ignition harnesses are not in themselves a source of interference. However, they can serve as means of radiation from interference sources. Steep transients are present in the interconnecting wiring in the ignition system; this is due to the action of the spark plugs, distributor, and breaker points. Even though these components may be well shielded, the interconnecting wiring can radiate the interference. As much care must be taken with the suppression of interference emanating from the interconnecting wiring as with the components themselves.

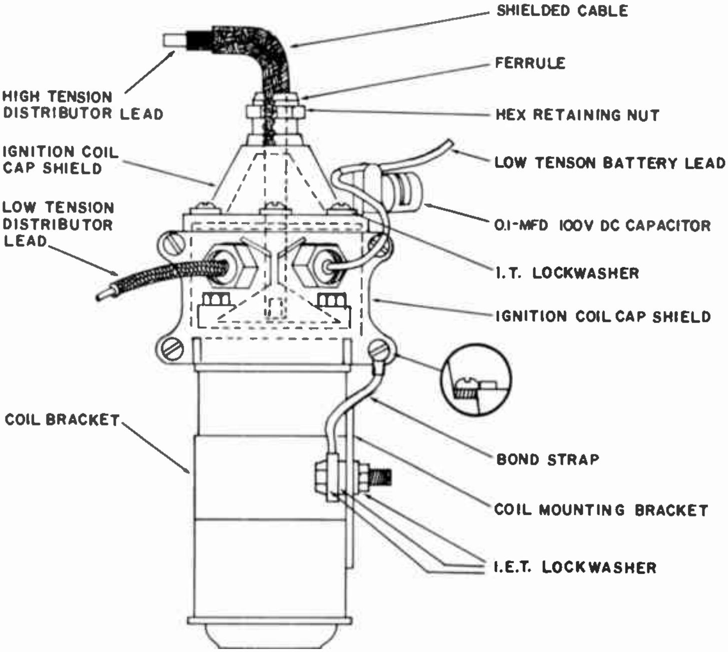


Fig. 10-7. Ignition-coil shield and capacitor installation.

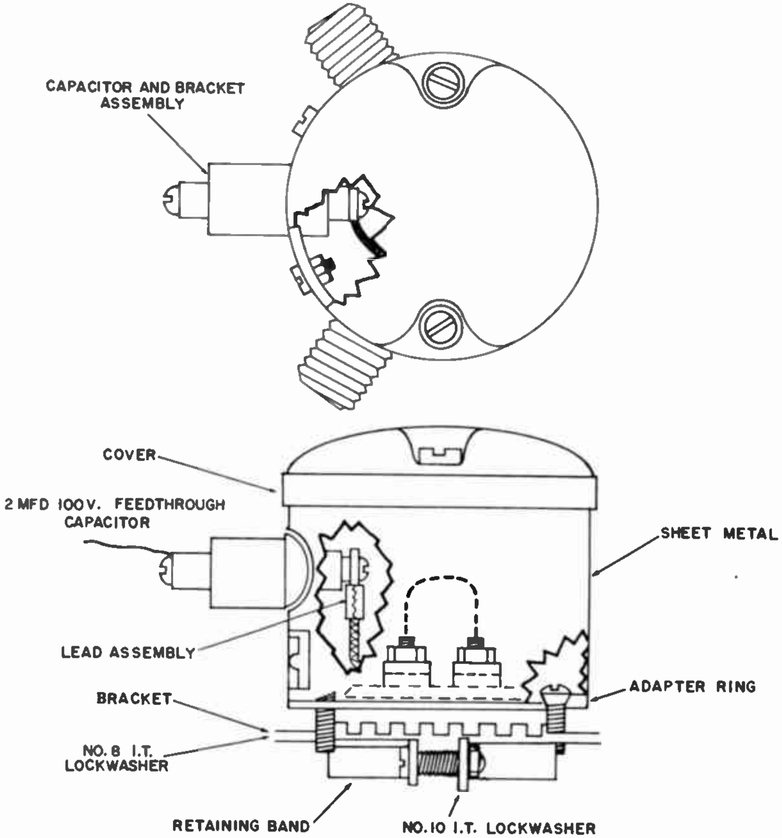


Fig. 10-8. General-purpose coil shield, showing feedthrough capacitor.

The ignition harness can be divided into high-tension and low-tension wiring. High-tension wiring includes the lead from the coil to the distributor and from the distributor leads to the spark plugs. The low-tension wiring includes the battery supply and breaker-point lead to the coil. The high-tension wiring in the secondary circuit is the more important because of the higher voltages and steeper transients involved. These transients can be reduced by installation of resistor suppressors in the secondary circuit; however, some degree of shielding is necessary for the high-tension wiring, to prevent radiation of interference.

Shielding for high-tension wiring may vary in construction. It may be nothing more than low per cent coverage, loosely woven wire braid with relatively poor shielding effectiveness.

Or it may be double and even triple layers of wire braid and completely solid-wall conduit. In the latter, shielding effectiveness may be increased to any desired degree by increasing the wall thickness. The degree of shielding is naturally dependent on the amount of interference that necessitates suppression.

Flexible shielding conduit gives high per cent coverage and is effective in preventing the radiation of interference from ignition wiring. It is made of strip metal formed either into spiral bellows or into some other kind of spiral that allows interlocking of adjacent strips. It may either be soldered at the seams or be allowed to provide sliding action between turns. For more effective shielding, it may be covered with woven metal braid.

The addition of resistor suppressors in the secondary circuit makes it possible to substitute tinned-copper braid (which is less expensive and requires less care in maintenance) for flexible conduit shielding. Fig. 10-9 shows the construction of tinned-copper braid shielding for high-tension ignition cables.

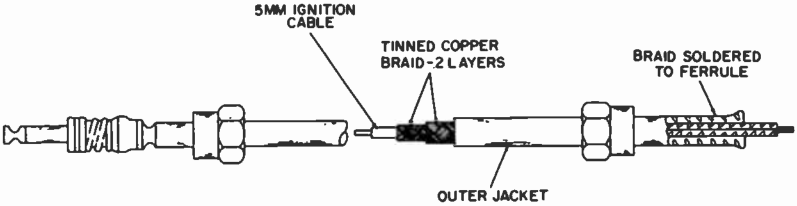


Fig. 10-9. Construction of tinned copper-braid shielding for high-tension ignition cables.

Braided-ignition cables provide adequate shielding when installed in conjunction with integrally suppressed spark plugs and ignition units.

The low-tension wiring is less of an offender in the radiation of interference from the ignition system; however, it still necessitates careful consideration because of the interference resulting from the make-and-break contact action of the breaker points.

The battery supply lead to the coil does not need shielding, because of the capacitor installed at the coil. The transients in the lead from the breaker points to the coil cannot be suppressed without interfering with the operation of the system; therefore shielding of this lead is necessary. A single layer of tinned-copper braid shielding is adequate in most installations.

By incorporating the coil and distributor in a single shield (the preferred method), the low-tension wiring requires no shielding. The wiring from the coil to the breaker points is entirely enclosed within the shield, and the battery supply lead is free of interference, being filtered by the action of the capacitor.

The maximum over-all effectiveness of a metallic shield can only be realized as long as there are no openings through which RF currents may escape—either by flowing along the outer surface of the shield, or by direct radiation. Joints and cable connections must therefore be carefully designed to insure good electrical contact along a continuous line.

MAGNETOS

The magneto is a self-contained electric generator designed to furnish electrical energy to the spark plugs during operation of an internal-combustion engine. Completely independent of any exterior source of electrical or chemical power, a magneto depends solely upon mechanical energy.

The magneto encompasses the functions of the generator, battery, distributor, breaker points, and induction coil of the battery ignition system. It accomplishes this by combining the three separate functions of current generation, voltage transformation, and spark distribution.

There are many different magneto designs, but the development of exceedingly powerful permanent magnets has led to the general usage of magnetos with revolving magnets. The two methods of spark distribution in a magneto design are the use of brush-type distributors and the use of jump-spark distributors. For minimum interference generation, the former method is recommended.

By incorporating the functions of current generation, voltage transformation, and distribution into a single unit, the magneto eliminates the inter-connecting wiring between the distributor and coil of the battery system. This resembles a battery system using an ignitor. The suppression measures for the magneto system are essentially the same as for the battery system—use of resistor suppressors, capacitors, and shielding.

A 10,000-ohm resistor suppressor is installed at the spark plug; on magnetos with a jump-type distributor an internal resistor-suppressor is not required. An integrally suppressed, self-shielded spark plug is best. The installation of a resistor suppressor at the input to the distributor is more difficult than it was in the battery ignition system. This may entail modification of the magneto. The resistor suppressor can be integrally installed in the rotor or at the distributor center tower.

Any location between the secondary winding and the distributor-rotor output terminal serves the purpose of damping the transients in the secondary circuit.

As with the battery ignition system, the use of resistor suppressors will only reduce interference, not eliminate it. Preventing the radiation of RF interterference from the magneto system entails complete shielding of the magneto, the high-tension leads to the spark plugs, and the lead to the magneto switch. Low-impedance paths between sections of the magneto are assured by using high-conductivity gaskets of soft metal.

The type of distributor used by the magneto is a factor in the over-all effectiveness of the magneto shield. Jump-spark distributors must be operated in a ventilated housing, since an active oxidizing agent (ozone) is formed by the sparking across the distributor gaps. Care must be taken that these louvers are well screened to prevent the leakage of interference. Since sliding contact is made by carbon brush distributors, high-voltage sparking is reduced to negligible proportions, and it is possible to completely seal the magneto and thereby minimize the possibility of leakage. The shielding of the high-tension leads to the spark plugs is similar in the magneto and battery ignition systems. The use of resistor suppressors in the high-tension circuit makes shielding conduit unnecessary; braided shielding is adequate.

The lead from the magneto to the ignition switch is a source of interference mainly because of its length and it should be shielded if no other suppression measures are taken. Shielding the lead, however, is not the most economical suppression measure; installation of a feedthrough capacitor through the magneto housing is equally effective and considerably cheaper.

CHAPTER 11

Suppression at the System Level

Special RF interference problems frequently arise in a large installation. These problems cannot be solved entirely by suppressing individual components, as described in the earlier chapters. Some of them arise from interaction between components that are close together. Others are due to common ground impedances, or to coupling between wires that are bundled together. RF interference problems are particularly severe in installations that include both interference sources and sensitive equipment that are receivers of the interference. Such installations require more complete shielding than is otherwise necessary. Bonding of each component to the structure or supporting frame becomes of major importance in such instances.

The examples treated in this chapter are representative rather than exhaustive. Obviously there are so many types of electronics equipment that it is impossible to cover them all in a book of this size. Although each type of equipment does introduce special problems of its own, the examples given here (together with the background material supplied in the earlier chapters) should be sufficient to allow suppression of practically any RF interference, provided no entirely new principle of RF interference generation is involved.

EQUIPMENT SUSCEPTIBILITY

RF interference susceptibility causes equipment to malfunction when any external lead or circuit (except the antenna) is subjected to an RF voltage. The term *susceptibility* can be expanded to include also that characteristic which causes equipment to malfunction when any power lead is subjected to an AF voltage. It is necessary, therefore, that the susceptibility of electronic equipment be carefully measured according to this restricted definition. Otherwise, the antenna or its lead-in may pick up interference.

The broad objective of susceptibility-limit requirements is to insure that electronic equipment will operate properly when exposed to the highest possible levels of interference in the operating area. Since these levels are not always known, equipment must be designed with the least susceptibility that is practical. There is always a point of balance between interference suppression at its source and reduction of susceptibility at the receiver.

The first step is to develop test procedures in accordance with susceptibility-control requirements. The second is to determine the highest practical degree of susceptibility control. The latter should therefore be considered in the equipment design. The susceptibility test procedure includes one or more of the following three actions:

1. Subjecting the equipment under test to a strong radiated continuous-wave (CW) field varied over a wide range of frequencies.
2. Subjecting the equipment to a strong radiated broad-band interference field.
3. Applying RF sine-wave signals conductively to all power leads.

Susceptibility Tests

Susceptibility is the characteristic of equipment to develop a change in operation or output indication due to the reception of undesired RF signals, produced by other equipment, via the case, interconnecting cables, antenna, lead-in, or power lines.

The susceptibility test consists generally of applying an intense magnetic field to selected parts of electronic equipment. This field is generated by an electrostatically shielded loop probe and powered by a standard signal generator through a 50-ohm cable which is always properly terminated at the generator end. The susceptibility of equipment to this source, in terms of microvolts, may be plotted against frequency for comparison with the susceptibility of other equipment. In this way, the best control requirements can be determined. Because of the intense magnetic field generated, the effect can be duplicated with a receiver and an interfering signal from a transmitter.

The attenuation of electric fields from 0.15 to 1000 mc by metal shielding material greatly exceeds that for magnetic fields. Therefore, the equipment under test must be subjected to magnetic fields of sufficient amplitude. (An electric field is an electromagnetic field in which the magnetic intensity is negligibly small. Likewise, a magnetic field is an electromagnetic field in which the electric intensity is negligible.)

This susceptibility-determining method makes it possible to simulate the effect of the highest levels of interference within an area from 0.15 to 1000 mc; it is desirable that the established limits should be related to these levels. However, there is no known equipment that can withstand the interference created by high-powered transmitters. As a result, the criterion for establishing interference-susceptibility limits depends on the levels of interference that the best designed equipment in the particular installation can tolerate.

The standard signal source has an impedance of 50 ohms. It is necessary to calculate the open-circuit voltage at the end of the 50-ohm cable connected to the signal source. Any standard signal generator with a 50-ohm source impedance is especially suitable because the open-circuit voltage is twice the output indication, regardless of the length of the output cable (cable losses neglected). Signal generators having source impedances of other than 50 ohms must be modified with appropriate pads to match the 50-ohm output cable. However, the open-circuit voltage at the end of the output cable will not be twice the output indication but must be calculated. A typical termination network is shown in Fig. 11-1.

Here is the procedure for determining susceptibility: The equipment under test is subjected to magnetic fields from 0.15 to 1000 mc generated by a three-inch, single-turn electrostatically shielded loop probe terminated by a 20-foot RG-8/U cable attached to a standard signal generator. The loop probe is secured to the most susceptible area of the equipment being tested. (The area of maximum susceptibility will be almost constant with changes in frequency.) Therefore, the equipment need not be probed with every change in frequency.

In order to determine the most susceptible area of the equipment, the following preliminary tests are necessary:

1. The loop probe is secured near the case of the equipment under test, at either the antenna input connector, any large opening, or the power-line entry. The signal generator is then set at maximum output and the spectrum scanned until a maximum leakage frequency is found.

(During scanning, checks are made at equipment operating frequencies. Then the entire device is probed at this maximum leakage frequency and a point of maximum susceptibility is located.

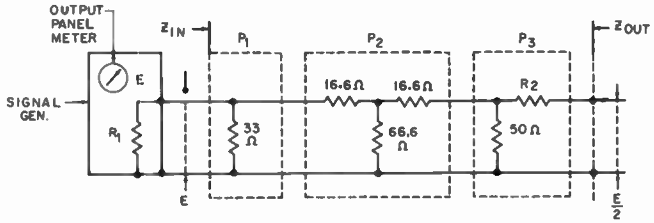
2. The loop probe is placed near the point of maximum susceptibility (as just determined) oriented for maximum coupling, and permanently secured.

Next the frequency range of the generator is again scanned with maximum output. If susceptibility is observed during the scanning, the generator output (open-circuit voltage in microvolts) is decreased until threshold susceptibility is reached. This reading, in open-circuit microvolts, is then compared with the specified limits for the equipment. If the level is above the specified limits, the unit under test meets the requirements.

A typical test set-up for radiated susceptibility with the signal source (generator) located outside the screen room is shown in Fig. 11-2. Fig. 11-3 shows a typical set-up for conducted susceptibility tests. A screen room is desirable because it eliminates both ambient interference signals and difficulties due to generator leakage.

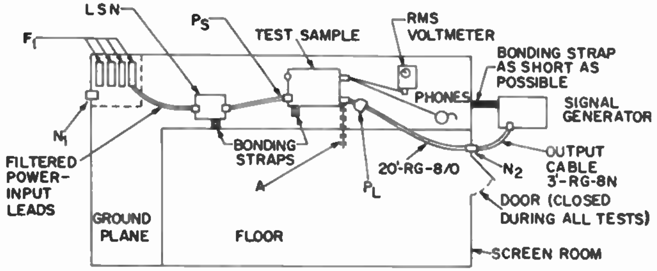
Undesirable response is a variance from the normal operation which does not cause malfunctioning of the equipment. *Threshold susceptibility* results in an undesirable response which is barely recognizable from the normal output.

It is not always possible to indicate specifically what change in normal output constitutes threshold susceptibility or the beginning of a malfunction. In most cases the threshold susceptibility, whether audible or visible, is taken as approxi-



P1—ten 330-ohm ¼-watt carbon composition resistors in parallel.
P2—six-db 50-ohm pad composed of ¼-watt carbon composition resistors.
P3—pad to make Z_{out} equal to 50 ohms; consists of ¼-watt resistors, including R2.
R1—20 ohms except at full output, where it varies from 10 to 50 ohms.
R2—250-ohm carbon composition resistor or network equal to 250 ohms.
Z_{in}—equal to generator output impedance.
Z_{out}—approximately 50 ohms.

Fig. 11-1. Network termination for signal generator.



A—antenna leadin either open wire or shielded, depending on equipment. If test sample operates with shielded leadin, termination is to a dummy load connected externally to a type-N fitting in filter panel. If open wire is used, termination is through type-N fitting to an antenna of a length so as to simulate antenna normally used with device under test.

F_1—screen-room filters for power input outside top deck.

LSN—line stabilization network used for each ungrounded power lead.

N_1—type-N fitting (2) installed in antenna-termination filter panel.

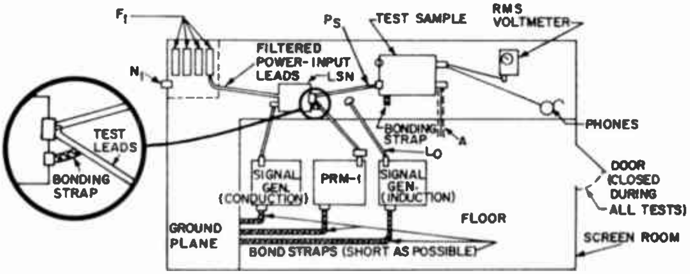
N_2—type-N fitting installed in screen-room door.

P_L—loop probe oriented for maximum output on meter or in phones, and permanently secured at, or very close to, antenna input fitting.

P_s—test sample power leads; 24 inches ±1 inch, spaced 2 inches apart, and 2 inches above ground plane.

Fig. 11-2. Typical setup for radiated susceptibility tests.

mately a 1-db change in output. The threshold of malfunctioning is usually taken as a point where it is difficult to distinguish between the effect of desired and undesired signals. In some equipment, threshold susceptibility actually cannot be determined because the equipment will malfunction if it is at all susceptible. In general, the performance requirements should be used as a guide for RF-interference susceptibility tests.



A—antenna leadin (see Fig. 11-2).

F_1—screen-room filters for power input located outside top deck.

L_o—output cable; 20' of RG-8/U with loop probe at end; probe placed for maximum output at meter or phones.

LSN—line stabilization network.

N_1—type-N fitting (see Fig. 11-2).

P_s—test sample power leads (see Fig. 11-2).

Fig. 11-3. Typical setup for conducted susceptibility tests.

In addition to the test for radiated fields, it is necessary to check for the effect of conducted signals feeding through power lines. These tests are the same as those described in earlier chapters.

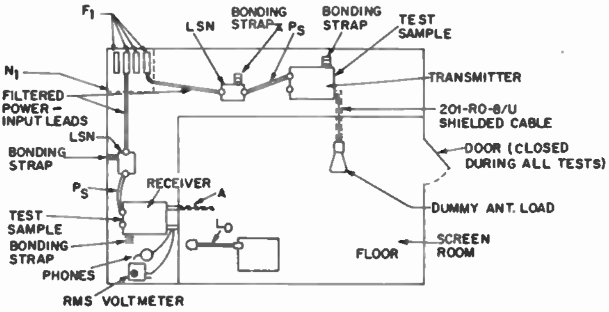
Susceptibility Reduction

Electronic equipment is susceptible to interfering signals which enter through metallic cases, interconnections, cables, power lines, antenna lead-ins, etc. A good example of the setup for investigating receiver susceptibility to transmitter leakage is shown in Fig. 11-4. There are a number of poor designs, and even proper ones, which can cause the equipment to be less or more susceptible to interference.

Shielded lead-ins—The susceptibility of receivers decreases considerably when shielded lead-ins are used, such as generally found on equipment operating above 30 mc. Receivers which operate below 30 mc should also be designed to use shielded lead-ins.

Shielded Cables—Shielded cables considerably attenuate the interfering signal and reduce susceptibility; this can be offset by using a cable which offers maximum attenuation. At 270.0 mc, for example, RG-8/U provides attenuation of 26 db less than RG-9/U, and RG-9/U provides 15.8 db more attenuation when encased in aluminum conduit.

Power- and Control-Line Filters—Unshielded leads, power cables, and control lines are very serious means of interference transmission. These wires will conduct both radiated and



A—antenna leadin (see Fig. 11-2).
F_1—screen-room filters.
L_o—generator output cable.
LSN—line stabilization network.
N_1—type-N fitting.
P_s—test sample power leads (see Fig. 11-2).

Fig. 11-4. Typical setup for testing susceptibility of receivers to transmitter leakage.

conducted interference into receiver circuits if proper precautions are not taken. Well-designed filters that are permanently installed within the receiver case at the point of entry for each wire will provide adequate decoupling between these wires and the receiver circuits. Similar filters can be employed in the case of lines leading out of the case which may be carrying interference generated within. These filters were discussed in Chapter 5.

Gasketing Materials—An equipment case composed of a sufficiently thick, continuous metallic enclosure containing no holes (front panel excluded) provides much more than 100-db attenuation. This attenuation can be nullified however, by the use of poor gasket material between the enclosure case and front panel. Often ordinary rubber embedded in a groove is used, and it leaves a continuous open seam through which interfering signals can penetrate. A rubberized metal gasket should be used instead. (For example, the aluminum mesh rubber impregnated gasket made by Connecticut Hard Rubber Company or the metal textile gasket made by Metal Textile Company.)

Front Panel—A great variety of devices are mounted on front panels of electronic equipment. These include phone jacks, fuse holders, meter jacks, control shafts, panel meters and other components which are often good paths of entry for RF interference. Also, front panels are usually poorly designed for suppression. Because a large amount of interference can enter the equipment through the front panel, the suppression techniques employed throughout the circuits and the case are sometimes nullified by poor front panel design.

Transmission-Line Connectors—On all shielded transmission lines, the maximum point of leakage is in the *N* connector which is mounted at the equipment case. Good clean connector surfaces are necessary, as is sufficient pressure at this point to maintain good contact to prevent leakage.

Ventilation Holes—Screening and louvers in the equipment case constitute serious leakage points. Ventilation can be provided more effectively and susceptibility reduced by the use of wave-guide types of ventilation holes.

Correctives Within the Equipment—The many techniques already discussed in the foregoing chapters and paragraphs are generally quite effective in reducing the susceptibility of electronic equipment. However, sometimes certain interference does get through, and in such instances special circuits can be employed. Among these are squelch circuits, noise limiters, blankers, and similar configurations.

VEHICLES

In cars, busses, trucks, locomotives, construction equipment, and other land-operated vehicles, common sources of interference are the ignition systems, charging circuits, and switching devices.

Ignition interference is the most serious. Rotating machinery is also a serious source of interference; such machinery includes electric fans, blowers, heaters, sirens, and the DC generator in the battery-charging circuit. In some charging circuits an alternator with a rectifier replaces the DC generator. This system has the advantage of high-current output at low engine speeds, safe operation at high maximum engine speeds, and a rapid rise in output within a narrow engine-speed range. A suppression installation on a vehicle where a high charging rate is required at low cruising speeds is shown in Fig. 11-5.

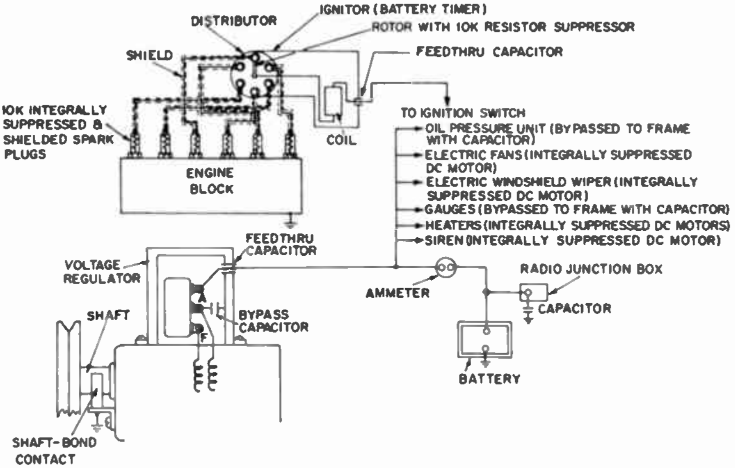


Fig. 11-5. Typical suppression system for vehicles.

Switching devices include voltage regulators, relays, and manual switches for the ignition, heater, blower, etc. Suppression of this type of interference was discussed in Chapters 7 and 10.

Static electrical discharges can be reduced by proper bonding. These static charges are built up from the action of rubber tires on the roadway and also from the action of the fan belt. The static electricity may arc between adjoining members and thereby cause RF interference.

A small pickup loop may be used with interference-measuring equipment for analysis of the electrical system of a vehicle. The following principal types of interference are present in vehicles using internal-combustion engines.

1. Pulse type interference due to spark discharge across spark-plug gaps.
2. Pulse type interference due to spark discharge between the distributor rotor and cap contacts.
3. Semipulse-type interference due to interrupted breaker-point currents.
4. Hash-type interference due to commutator arcing in the battery-charging generator.
5. Hash-type interference due to the vibrating contacts of the battery-charging regulator.

The RF interference radiated from a vehicle is evaluated by making measurements with both a pickup-loop probe and rod and dipole antennas. After various locations throughout the vehicle are checked with the pickup loop probe, a good analysis of the interference can be made by checking around the wires beneath the dash, the high-tension leads over the distributor, and the heavy cables from the battery to the starter switch. These measurements are made three feet from the inside of the motor compartment and one foot above the radiator.

Various types of interference are distributed over the frequency spectrum in the following manner:

1. Pulse-type, due to spark discharge, found over the entire frequency spectrum.
2. Semi-pulse type, due to interrupted breaker-point current, found between 15 and 250 kc.
3. Hash-type due to the generator or voltage regulator, found from 15 kc to 5 mc.

The pickup-loop probe method can be used in lieu of measuring the actual radiated interference, so long as only a relative indication is necessary. The radiated interference from a shielded vehicle is so low that accurate measurements with rod and dipole antennas are not practical over most of the frequency range. The pickup-loop probe method similarly has a measurable interference level over only a very low- and very high-frequency portion of the spectrum. If the measuring instrument is tuned alternately to 500 kc, 7 mc, 20 mc, and

100 mc (the frequencies of maximum radiation with ineffective or no shielding), and the RF interference is low, the shielding will also be adequate at all other frequencies. It is important that measurements be made at these frequencies. Here the interference amplitude is greatest, and there is less possibility of random pickup from other sources.

An instrument bandwidth great enough to pass the high-frequency sidebands of pulse-type interference is desirable. In this way, readings of sufficient magnitude to permit use of a low sensitivity input circuit will be produced. The meter should have the following characteristics:

1. Four non-tunable bands 200 kc wide, each centered 500 kc, 7 mc, 20 mc, and 100 mc.
2. A high-gain 200-kc bandwidth, 20-mc IF strip composed of single-tuned circuits to minimize overshoot.
3. A superheterodyne receiver on 500 kc, 7 mc, and 100 mc, and a straight-through tuned-RF–type receiver on 20 mc.
4. Two tuned circuits with less than critical coupling ahead of the mixer.
5. A detector driver of the power-pentode type, to handle peak amplitudes without overload.
6. A quasi-peak–type metering circuit.
7. A meter calibrated in db with 0 db at center scale.
8. A built-in interference source to permit the gain of the instrument to be set, with a potentiometer, for a meter reading of 0 db on any given band. This will make up for gain variations due to tube, line-voltage, and other variations, and should allow a check of proper instrument operation.

The interference-pickup device should be a low-frequency loop probe. It should be mounted in such a manner that the hood of the vehicle under test can be closed in order to minimize random pickup.

Aural monitoring should be included so that if other interference is suspected, the vehicle engine can be turned off and the aural indication listened to in the earphones. This will insure that the interference is coming from only the vehicle under test.

This instrument should have a self-contained AC power supply which can be easily removed and replaced with batteries. Subminiature construction techniques are often used to reduce the size and cost and to make the instrument more shock resistant.

ENGINE-DRIVEN EQUIPMENT

Engine-driven equipment includes cranes, concrete mixers, road graders, and road rollers. Since their suppression systems are likely to be similar, only one example will be described in detail here.

This 20-ton crane consists of the carrier and the truck-mounted crane, each driven by a six-cylinder gasoline engine having a battery ignition, battery charging, and hand-cranking system.

Carrier-Engine Suppression

1. Each spark plug is integrally shielded and suppressed.
2. The distributor is surrounded by a metallic shield.
3. The ignition-coil terminals are enclosed in an ignition-coil assembly.
4. The primary terminal of the ignition coil is bypassed to the ignition-coil assembly through a 0.1-mfd 100-VDC capacitor with one cadmium-plated tooth-type lockwasher.
5. Each high-tension lead is shielded with tinned copper braid terminated at the spark plugs, distributor shield, and coil shield with appropriate threaded fittings.
6. A 10,000-ohm resistor suppressor is inserted into the high-tension coil-distributor lead at the distributor shield.
7. The low-tension lead from the ignition coil to the distributor is shielded with tinned copper braid terminated at each end with appropriate threaded fittings.
8. The ignition-coil assembly is bonded to the engine by a tinned copper braid strap and cadmium-plated tooth-type lockwashers.
9. The ignition-coil bracket is bonded to the coil mounting bracket by plated tooth-type lockwashers.
10. The ignition-coil mounting bracket is bonded to the engine by plated tooth-type lockwashers.
11. The distributor-shield assembly is bonded to the engine by a tinned copper braid strap and cadmium-plated tooth-type lockwashers.
12. The low-tension lead between the ignition switch and ignition coil is shielded with tinned copper braid terminated at the coil assembly and instrument panel by clamps. Each clamp is bonded by cadmium-plated tooth-type lockwashers.
13. The armature terminal of the battery-charging generator is bypassed to the generator housing through a 0.1-mfd 100-VDC capacitor with plated tooth-type lockwashers.

14. The generator end plates are bonded to the generator mounting bracket by four cadmium-plated tooth-type lockwashers.
15. The generator mounting bracket is bonded to the engine block by one plated tooth-type lockwasher.
16. The armature terminal of the regulator is bypassed to the regulator bracket by a 0.1-mfd 100-VDC capacitor and plated tooth-type lockwasher.
17. The battery terminal of the regulator is by-passed to the regulator bracket through a 0.1-mfd 100-VDC capacitor with plated tooth-type lockwashers.
18. Each armature and field lead is enclosed in tinned copper braid shielding terminated in clamps, and bonded at the regulator mounting bracket and generator by tooth-type lockwashers.
19. The battery lead from the voltage regulator to the ammeter is shielded with tinned copper braid terminated at each end in clamps. The lead is grounded at the voltage-regulator mounting bracket and instrument panel by plated tooth-type lockwashers.
20. The engine is bonded to the front crossmember by a tinned copper braid strap and plated tooth-type lockwashers. The top section of the hood is bonded to the solid portion by a tinned copper-braid strap and plated tooth-type lockwashers.

Crane-Engine Suppression

1. Each spark plug is integrally shielded and suppressed.
2. The distributor is surrounded by a metallic shield.
3. The ignition-coil terminals are enclosed in an ignition-coil assembly.
4. The primary terminal of the ignition coil is bypassed to the ignition-coil assembly through a 0.1-mfd 100-VDC capacitor with one plated tooth-type lockwasher.
5. Each high-tension lead is shielded with tinned copper braid terminated at the spark plugs, distributor shield, and coil shield with appropriate threaded fittings.
6. A 10,000-ohm resistor suppressor is inserted into the high-tension coil lead at the distributor shield.
7. The low-tension lead from the ignition coil to the distributor is shielded with tinned copper braid terminated at each end with appropriate threaded fittings.
8. The ignition-coil assembly is bonded to the engine by a tinned copper braid strap and plated tooth-type lockwashers.

9. The ignition-coil bracket is bonded to the coil-mounting bracket by plated tooth-type lockwashers.
10. The ignition-coil mounting bracket is bonded to the engine by plated tooth-type lockwashers.
11. The distributor-shield assembly is bonded to the engine by a tinned copper braid strap and plated tooth-type lockwashers.
12. The armature terminal of the battery-charging generator is bypassed to the generator housing through a 0.1-mfd 100-VDC capacitor and plated tooth-type lockwashers.
13. The generator housing is bonded to the adjusting-arm support bracket by a tinned copper braid strap and tooth-type lockwashers.
14. The adjusting-arm support bracket is bonded to the engine block by plated tooth-type lockwashers.
15. The regulator base is bonded to the regulator mounting bracket by a tinned copper braid strap and plated tooth-type lockwashers.
16. The battery and armature terminals of the regulator are bypassed to ground by 0.1-mfd 100-VDC capacitors, and the capacitor mounting brackets are bonded to the regulator base by plated tooth-type lockwashers.
17. The regulator mounting bracket is bonded to the engine by plated tooth-type lockwashers.
18. Each armature and field lead is enclosed in tinned copper braid shielding terminated in clamps and bonded at the regulator and generator by plated tooth-type lockwashers.
19. The instrument-panel mounting bracket is bonded to the frame of the upper structure.
20. The instrument panel is bonded to its mounting bracket.

ENGINE-GENERATORS

Engine-generators vary from small auxiliary units, used to supplement the power plants of airplanes and vehicles for starting purposes, to large units which furnish the power for cities or even entire countrysides.

The RF-interference-producing elements of an engine-generator include the driving engine, main generator, exciter, charging generator, and the voltage and current regulators. Not all of these items are present in any particular unit. For example, in certain engine generators the field flux is provided by revolving permanent magnets; this method of excitation minimizes interference from the exciter circuit since no commutator ripple or brush sparking exits. Some units have inherently interference-free voltage regulators; others have no voltage regulators at all. Each suppression system must therefore be designed for the particular engine-generator.

Many engine-generator units are driven by gasoline engines, and their battery or magneto ignition systems are sources of severe interference (its suppression is discussed elsewhere in this chapter). Small engine-generators used as battery chargers employ an integrally shielded and suppressed spark plug, and a shielded high-tension lead. Engine-generators with rated output of 10 KW or greater often use diesel engines, thus eliminating ignition interference.

The main generator can produce interference from brush sparking at the collector rings and from harmonics in the AC output. The excitation for most engine-generators is provided either from a separate exciter mounted on the engine shaft, or from an auxiliary winding on the main generator armature. In either case, the exciting armature output must be commutated before being applied to the main generator field. (The suppression of commutator-type interference was discussed in Chapter 9.)

The charging-generator suppression problems are similar to those of the exciter, which also is essentially a DC generator. The latter was discussed in Chapter 9.

The control panel with its connecting circuits between meters, exposed stepping switches, and many other seemingly unimportant components can be the cause of considerable interference. Here the suppression measures described earlier in this book must be applied.

Voltage and current regulators which employ vibrating contacts should not be used in engine-generators. Alternate types as well as the suppression of vibrating types were discussed in Chapter 9.

The unit to be discussed is a 30-KW engine-generator consisting of a magneto ignition, a 6-cylinder engine(developing 60 hp at 1,800 rpm and driving a rotating field), a belt-driven generator (30 KW 37.5 KVA 3-phase, 50-60 cps, 120/208 VDC), and a positive-ground regulator. The control panel and box can be removed as a unit without removing any other generator component.

Suppression Measures

The following RF-interference-suppression measures are adequate, but they can be improved by incorporating certain suppression measures in the original design. The magneto stop switch lead and the regulator lead to the rheostat, for example, need not be shielded if feedthrough capacitors are installed in these leads, through the magneto and regulator shields.

1. Each spark plug is integrally suppressed and shielded.
2. The magneto is shielded and suppressed.
3. Each high-tension lead is enclosed in tinned copper braid shielding and terminated in appropriate elbows, ferrules, and retaining nuts.
4. The low-tension magneto shut-off lead is enclosed in tinned copper braid shielding, with the appropriate ferrule and retaining nut at the magneto and a clamp to ground at the shut-off switch end. The clamp is bonded with tooth-type lockwashers.
5. The magneto shut-off lead is to the right side of the chassis and bonded each foot and a half by plated clamps to the engine block, bulkhead, and frame. The clamps are bonded by tooth-type lockwashers under the clamp or between it and the screw head.
6. The lead from the magneto shut-off switch to the emergency shut-off relay is enclosed in tinned copper braid and is connected to the control panel box by clamps at each end. The clamps are bonded with tooth-type lockwashers.
7. The magneto is grounded to the engine block by a tinned copper braid strap from the magneto cover screw to the oil-pan bolt and from the magneto mounting bolt to the timing-gear case.
8. The timing-gear case is bonded to the skid base by a tinned copper braid strap and tooth-type lockwashers.
9. The battery-charging generator is bonded to the engine block by tooth-type lockwashers. The shield of the battery-charging regulator also is bonded to its mounting bracket by tooth-type lockwashers.
10. The adjusting arm of the battery-charging generator is bonded to the generator and engine block by tooth-type lockwashers. The mounting bracket of the battery-charging regulator shield also is bonded to the engine block by tooth-type lockwashers.
11. The battery-charging regulator is enclosed in a metal box, with provision for terminating the shielding of the field lead. Feedthrough capacitors are used in the battery and armature leads.
12. The armature terminal of the regulator is bypassed by a bulkhead feedthrough capacitor.
13. The battery terminal of the battery-charging regulator

is bypassed by an 0.1-mfd 100-VDC bulkhead feedthrough capacitor.

14. The lead from the generator field terminal to the battery-charging regulator shield is enclosed in tinned copper braid shielding and terminated in a clamp bonded to the generator frame with tooth-type lockwashers. At the regulator shield the lead is terminated by an appropriate ferrule and retaining nut.
15. The brush rigs of the exciters are bypassed to the frame by 0.1-mfd 500-volt AC/DC capacitors.
16. The collector-ring brush rigs of the main generator are bypassed to the generator by 0.1-mfd 500-volt AC/DC capacitors.
17. The leads from the exciter armature and field are separately shielded in tinned copper braid to the AC regulator, field rheostat, and On-Off switch. The shielding is bonded by clamp connections and tooth-type lockwashers.
18. The leads from the alternator to the terminal board in the control panel are as short as possible and are routed close to the side of the panel box, *away* from the control wiring.
19. The base of the AC voltage regulator is bonded to the control-panel box by tooth-type lockwashers.
20. Each leg of the line at the load side of the main circuit-breaker switch is bypassed by a 0.1-mfd 500-volt AC/DC capacitor.
21. The mounting bracket of each capacitor is bonded to the control-panel box by tooth-type lockwashers.
22. The control-panel box is bonded to the frame by a tinned copper braid strap and tooth-type lockwashers.
23. The control panel is bonded across the hinge to the control-panel box by a tinned copper braid strap and tooth-type lockwashers.
24. The unit shroud is bonded to the skid base by tooth-type lockwashers.

DIESEL ELECTRIC LOCOMOTIVE

Diesel electric locomotives have all but replaced steam locomotives for both freight and fast passenger service. However, they present a serious interference-suppression problem because of their large generators and motors.

Diesel electric locomotives usually contain one or two water-cooled diesel engines, and four to six DC traction motors. One or two main generators, mechanically coupled to the diesel engines, supply power to the traction motors. One or two auxiliary generators, also coupled to the diesel engines, are used for charging the locomotive storage batteries and as a low-voltage power supply. In addition, there are one or two voltage regulators, a fuel-pump motor, a cab heater, and gauges. Heavy-duty locomotives also carry one or two hot-water heaters for preheating the diesel engines and associated components during cold weather, and a steam generator for trainline heating. Except for the diesel engines, all these components are potential sources of interference—either individually or by interaction.

The following is a description of a RF-interference suppression system in a typical eight-ton Diesel-electric switching locomotive.

1. The armature terminals of the battery-charging generators are bypassed to the generator housing through 0.1-mfd 100-VDC capacitors with tooth-type lockwashers.
2. Two 0.25-mfd 100-VDC capacitors are connected in parallel across the generator terminals of the regulators.
3. One 0.1-mfd 100-VDC capacitor is applied across the voltage-regulator contact points.
4. One 0.1-mfd 100-VDC capacitor is applied across the battery terminals in the regulator box.
5. One dry-disc selenium rectifier of adequate voltage and current rating is installed at the battery-charging regulator. The anode terminal of the rectifier is connected to the field terminal of the regulator, and the cathode terminal to the generator terminal.
6. The main-generator brushes are bypassed to the end-bell housing through two 0.1-mfd 500-VDC capacitors with two tooth-type lockwashers.
7. Each brush of the cab-heater motor is bypassed to the motor frame inside the end bell through a 0.1-mfd 250-volt AC/DC capacitor with two tooth-type lockwashers.
8. The armature and the field leads from the charging generator are individually shielded by tinned copper braid with clamp connections and one tooth-type lockwasher at each end.
9. The charging-generator mounting bracket is bonded to the engine block by four tooth-type lockwashers.
10. The charging-generator housing is bonded to the generator mounting bracket by four tooth-type lockwashers.
11. The regulator mounting bracket is bonded to the engine mounting bracket by two tooth-type lockwashers.

12. The regulator is bonded to the mounting bracket by eight tooth-type lockwashers.
13. The regulator cover is bonded to the regulator box by two tooth-type lockwashers.
14. Each of the four traction motors is bonded to the locomotive frame by a tinned copper braid strap and two tooth-type lockwashers.
15. The regulator is bonded to the mounting bracket by a tinned copper braid strap and two tooth-type lockwashers.
16. The cab-heater motor is bonded to the mounting bracket by a tinned copper braid strap and two tooth-type lockwashers.
17. The motor support bracket of the cab heater is bonded to the heater shell by ten tooth-type lockwashers.

TELETYPEWRITERS

Teletypewriters are telegraph printing instruments with a keyboard similar to that of a typewriter for sending messages, and motor-driven, signal-actuated mechanisms for printing the received messages. The major sources of interference are the switching devices and the motors. In one example, a 110VAC-operated, lightweight teletypewriter, objectionable RF interference was noted between 0.55 and 70.0 mc. This interference was emanating from the motor, the breaker points on the governor contacts, and the distributor contacts. The suppression system described below attenuated this interference successfully (Fig. 11-6).

1. Bonding.
    a. Bond straps are applied across each shock mount.
    b. A lead gasket is placed between the motor and the governor housing.
2. Shielding.
    a. All leads are replaced by shielded wire.
    b. The AC power cords are shielded.
3. Insulated sleeving.
    a. Leads from fuses to the 20-ohm receiver are covered with insulated sleeving, and chokes are inserted in the connecting leads.
    b. All leads from binding posts to cable are covered with insulated sleeving.
4. Capacitors.
    a. Motor brushes are bypassed to ground through 0.01-mfd 250-volt AC/DC capacitors (with 1-inch leads).

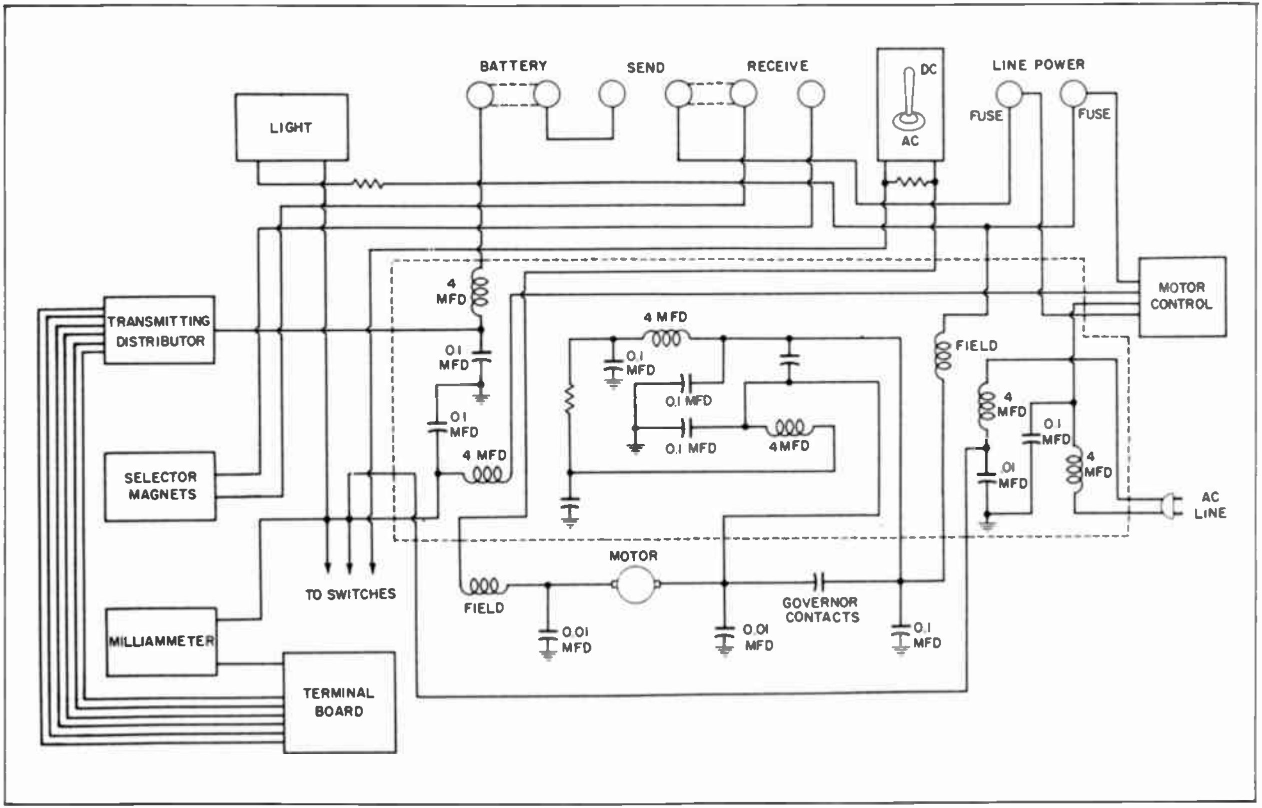


Fig. 11-6. Wiring diagram of teletypewriter with suppression components installed.

The capacitors are grounded to the motor end-bell housing.

   b. The generator contact is bypassed to the metal shield through a 0.01-mfd 250-volt AC/DC capacitor (with 1 inch leads); the capacitor is grounded under a mounting screw.

5. Filter Box.
   The filter box is bolted to the rear of the teletypewriter. (The container is divided into compartments.)
6. Filters.
   a. A dual-type filter consisting of two 4-microhenry chokes and two 0.1-mfd capacitors is installed at the power input. The capacitors are installed in the motor power leads.
   b. A pi-type filter consisting of two 4-microhenry chokes, two 0.01-mfd capacitors, and two 0.1-mfd capacitors is installed in the governor control leads. The exist- 1.0-mfd 600-volt spark capacitor is installed in the filter box.
   c. An L-type filter consisting of two 4-microhenry chokes and one 0.1-mfd capacitor is installed between the distributor contact arm and the DC power terminal.
   d. An L-type filter consisting of one 4-microhenry choke and one 0.1-mfd 500-volt AC/DC capacitor is installed between the breaker points and the rheostat.

MARINE EQUIPMENT

Marine equipment on both large and small vessels may require interference suppression to insure reliable and interference-free communication and operation of the electronic navigational devices aboard them. Such vessels include harbor tugs; patrol and utility boats; passenger, pleasure, and cargo boats; barges and fishing craft. All of these vessels carry a large number of accessory equipment, which is a potential source of RF interference.

The motive power for such craft is usually provided by a diesel engine; therefore ignition interference is not a problem. Some smaller vessels, however, use a gasoline engine with an ignition system that must be suppressed. The earlier discussions on interference suppression in ignition systems is applicable to marine gasoline engines.

Rotating machinery is by far the most important source of interference in marine equipment. Included in this category are the charging generators, steering and windlass motors, and a variety of motors in refrigerators, fans, and air compressors. Of lesser importance only because of the fewer numbers involved are the voltage and current regulators and the cut-out relays. Their suppression was discussed in Chapter 8. The number of accessories carried usually depends on the size of the vessel; even with a small boat, however, rotating machinery must be properly suppressed.

In addition to interference-producing accessory equipment, many vessels carry communications equipment (discussed as an interference source in Chapter 5).

The main consideration here, however, is to keep both radiated and conducted interference out of the receiver circuits. This problem is magnified by the nearness of the receiver to the interference source, as well as by their sharing of the same power supply.

To illustrate a typical suppression system, as well as the varied equipment involved, the RF-interference-suppression system for a diesel-powered tug is presented below. This information may be used in interference suppression of any similar installation.

Main Diesel Engine With the 24-Volt Battery-Charging System

1. 24-volt DC generator.
    a. Each armature terminal is bypassed to the regulator shield through a 0.1-mfd 1000-volt capacitor.
    b. The generator housing is bonded to the mounting bracket with three tooth-type lockwashers.
    c. The generator mounting bracket is bonded to the engine block with six tooth-type lockwashers.
    d. Each capacitor mounting bracket is bonded to the regulator shield with two tooth-type lockwashers.
2. Regulator.
    a. Each generator terminal and the battery terminal is bypassed to the regulator shield with a 0.1-mfd 1000-VDC capacitor and two tooth-type lockwashers.
    b. The regulator shield is bonded to the engine by two tooth-type lockwashers.

Main Engine-Generator (120-VDC 5-KW Output, with 24-Volt Battery Charging System)

1. 24-VDC generator.
    a. Each armature terminal is bypassed to the generator housing through a 0.1-mfd 100-VDC capacitor and two tooth-type lockwashers.

   - b. The generator housing is bonded to the mounting brackets with four tooth-type lockwashers.
   - c. The forward generator mounting bracket is bonded to the engine with two tooth-type lockwashers.
   - d. The rear generator mounting bracket is bonded to the oil-filter support with one tooth-type lockwasher.
   - e. The oil-filter support is bonded to the engine with two tooth-type lockwashers.
2. Charging-system regulator.
   - a. The battery and armature terminals are bypassed through 0.1-mfd 100-VDC capacitors with tooth-type lockwashers.
   - b. The regulator mounting bracket is bonded to the engine with two tooth-type lockwashers.
3. 120-VDC 5-KW main generator.
   - a. Each top positive and negative brush rig is bypassed to the generator end bell through two 0.1-mfd 100-VDC capacitors and tooth-type lockwashers.
   - b. The main-generator housing is bonded to the skid base with four tooth-type lockwashers.
   - c. The four engine mounts are bonded to the skid base with eight tooth-type lockwashers.
4. Instrument panel.
   - a. The ammeter is bypassed to the instrument panel through a 0.1-mfd 100-VDC capacitor and two tooth-type lockwashers.
   - b. The instrument-panel cover is bonded to the panel with eight tooth-type lockwashers.
   - c. The instrument-panel base is bonded to the main-generator housing with four tooth-type lockwashers.
5. Shielded leads.
   - a. The three leads between the generator and regulator are enclosed in a tinned copper braid, terminated in clamps, and bonded with tooth-type lockwashers.
   - b. The leads from the regulator to the ammeter are enclosed in tinned copper braid, terminated in clamps, and bonded with tooth-type lockwashers.
   - c. The synchro-start overspeed-governor lead between the governor and the instrument panel is enclosed in tinned copper braid, terminated in clamps, and bonded with tooth-type lockwashers.

Shore Supply Motor-Generator

1. Generator motor (115-VAC induction-type); no suppression required.

2. Generator (1.5-KW 115-VDC). A 0.25-mfd 500-volt AC/DC capacitor is applied to each side of the line at the junction box on the unit. The junction box is bonded to the motor and generator bases with tooth-type lockwashers.

Windshield-Wiper Motor (115-Volt AC/DC)

The positive and negative brushes are each bypassed with a 0.1-mfd 250-volt AC/DC capacitor and tooth-type lockwashers.

Engine-Room Switchboard

A 0.1-mfd 500-volt AC/DC capacitor is applied across the navigation-panel terminals at the switchboard.

Electric Motors (115-120 Volts DC)

1. A 0.1-mfd 500-volt AC/DC capacitor is applied to each brush holder on the motors listed below. (Two capacitors are required for each motor and the pump.)
   a. Anchor-windlass motor.
   b. Air-compressor motor.
   c. Fuel-oil transfer pump.
   d. Engine-room supply motor.
   e. Engine-room exhaust motor.

(A tooth-type lockwasher is applied to each capacitor mounting bracket, and all motors are bonded to their mountings with plated tooth-type lockwashers and/or tinned copper braid straps.)

2. A 0.1-mfd 300-VDC capacitor is applied to each brush of the following motors. As before, two are required.
   a. Fresh-water pump motor.
   b. Exhaust-blower motor.
   c. Circulating-pump motor.
   d. Boiler-burner motor.
   e. Refrigerator motor.

The suppression system just described is applicable to a particular type of boat. It is illustrated to indicate typical suppression techniques on marine vessels. Each craft will need a suppression system designed specifically for it; however, the suppression principles outlined here and described earlier can be applied to any. The incorporation of integrally suppressed accessories will greatly alleviate the interference-suppression problem.

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