Some Techniques for the Elimination of Corona Discharge Noise in Aircraft Antennas*

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Summary—**Theories of noise generation and coupling are applied to the problem of devising techniques for the elimination of precipitation static interference in aircraft. The logical consequences of the theory are employed in devising several versions of a decoupled discharger capable of providing precipitation static noise reduction of 60 db. Optimum discharger locations are determined and successful flight tests of the dischargers are described. Various proposed discharger designs are considered in light of the coupling theory, and their performance when tested in the laboratory is discussed. Several antenna designs capable of providing precipitation static reduction on vehicles which do not permit discharger installation are proposed and tested in the laboratory. Electronic techniques for reducing precipitation static interference by operating on the signal at the receiver are considered.**

Although many of the proposed precipitation-static-elimination techniques are not entirely satisfactory, the decoupled dischargers and decoupled antennas work well enough that precipitation static need not pose a problem under normal flight conditions.

I. Introduction

Triboelectric charging,[1] occurring when an aircraft is operated in precipitation, raises the aircraft potential until corona discharges occur from points of high dc field on the aircraft. In a companion paper [1] it is shown that these discharges can produce sufficient *precipitation static* interference in aircraft LF and HF receiving antennas to disable communication and navigation systems. Since the loss of communication constitutes a serious flight safety hazard, investigators were prompted to devise methods for the elimination of this form of radio interference soon after radio communication equipment began to be used in aircraft.

Early workers [2], [3], [4] found that precipitation static was reduced through the use of shielded loop antennas on aircraft. (The reasons for the effectiveness of loops in reducing precipitation-static interference are discussed in Section III.) Since precipitation static still constituted a serious flight hazard, a joint Army-Navy precipitation-static project was initiated in 1943 [5], [6]. Several new methods of reducing radio interference were proposed. The most important of these were the use of wick dischargers and dielectric-coated antenna wire [6].

A thorough investigation was made of triboelectric charging using different materials in an attempt to eliminate or substantially reduce the charging rate by properly selecting coating materials for the aircraft [5], [6]. Such attempts were completely unsuccessful since triboelectric charging is a surface phenomenon, and a thin film of oil is sufficient to completely destroy any desirable properties that a coating might have [6].

Another approach to precipitation-static elimination is to operate on the noise signal after it has been coupled into the receiving antenna [7]. A noise "blanker" inserted in the circuit between the antenna and receiver would short out the receiver terminals as soon as a noise impulse appeared at the input to the blanker. The receiver terminals would remain short-circuited for the duration of the noise impulse. Limitations inherent in the use of blankers [8] are discussed briefly in Section V.

Many methods have been suggested for discharging the aircraft without generating noise in the receiving systems. Dana [9] proposed the "block and squirter" in which a discharger is maintained at a high AC potential with respect to the aircraft. The receiving circuits are blocked during the alternate half cycles during which discharges occur. Another system is the biased discharger in which a discharge is forced to occur between a point and a cylinder [10]. Discharging occurs when ions of the same polarity as the point are carried away by the airstream, while ions of the opposite charge are captured by the high fields of the point. Other proposed systems include flame dischargers, electron-gun discharge tubes, and direct thermionic emitters [11].

This earlier work indicated that efforts to prevent aircraft charging would not be successful, and that the following three general approaches to the problem of precipitation static elimination were possible:

1) Reducing the noise generated by the discharge noise source,
2) Reducing the coupling between the source and the receiver,
3) Operating on the received signal to eliminate the noise components.

Each of these approaches was considered, and methods for their implementation are discussed in the succeeding sections. Implementing either Method 1) or Method 2) does not require the use of active circuit elements between the antenna and the receiver. Because of their greater potential simplicity only these two methods

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[1] Triboelectric charging occurs whenever two dissimilar materials are placed in contact and then separated. In the case of an aircraft flying through precipitation containing ice crystals, the ice crystals generally acquire a positive charge, leaving the aircraft with a negative charge.

were studied in the laboratory or during flight tests.

The problems of noise generation and coupling [12] are best studied with the aid of the reciprocity relationship discussed in [1] and derived in [13] and [14]. For the conditions outlined in Fig. 1, the coupling theorem states that

$$I_2(\omega) = \frac{1}{V_1(\omega)} \int_{T_2} \boldsymbol{E}_1(\mathbf{x}, \omega) \cdot \boldsymbol{J}_2(\mathbf{x}, \omega) dv. \qquad (1)$$

The coupling relationship of (1) suggests several ways in which the noise content of the antenna current I_2 can be reduced or eliminated.

1) By causing the noise content of the discharge current J_2 to approach zero,
2) By causing the ratio $\boldsymbol{E}_1/V_1$ to approach zero (reducing the coupling),
3) By causing J_2 to be perpendicular to $\boldsymbol{E}_1$ (reducing the coupling).

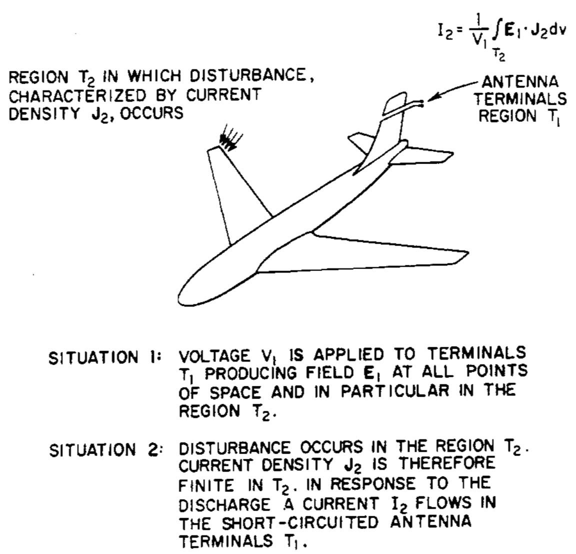

Fig. 1—Illustrating noise coupling theorem.

II. Dischargers

A. General

Dischargers are devices installed on an aircraft to permit current to be discharged without generating noise in the receiving system. In Sections II-B and II-C, the decoupled dischargers developed using the logical consequences of (1) are discussed. In Section II-D, various proposed discharging techniques are listed. Their probable success is discussed briefly in the light of (1).

B. Passive Decoupled Dischargers

To be effective, a discharger must discharge at sufficiently high rates that the aircraft potential remains below corona threshold for all other points on the aircraft. Hence, the discharger must be located in a region of high dc field intensity. Perversely, however, the regions of high dc field (such as the airfoil extremities) where corona discharges normally occur and where the dischargers must be located, also correspond to regions of high RF coupling fields [1]. For example, consider the field in a small region about the trailing edge of a wing, as in Fig. 2(a). The field configuration, either RF or static, is determined by the shape of the conductor forming the field boundary. To develop a satisfactory discharger, therefore, it is necessary to devise a scheme for causing a difference between the two fields. In particular, we would like a high dc field imposed upon the discharge point while the RF field at the point becomes zero. Tanner has suggested a technique for accomplishing decoupling in this way [15].

The way in which a region of zero RF coupling field can be produced is evident from Fig. 2(b), which shows a cross section of the trailing edge of an airfoil surface in which the rearmost portion is electrically isolated from the rest of the surface. There are two lines along the conductor on which the RF field is zero, and a considerable region over which the field is very small. If a discharge could be produced at the point of zero RF field, no noise would be coupled into the receiving system. To produce a discharge at the point of zero RF field, however, the isolated section must be maintained at the same dc potential as the rest of the aircraft. The requirements that the trailing edge be isolated at RF and directly connected at dc can be very closely approximated by connecting the trailing edge to the airframe through a very high resistance. If the value of the connecting resistance is high compared to the capacitive reactance between the isolated trailing edge and the remainder of the airfoil, the RF field will remain essentially as in Fig. 2(b), while the dc field in the immediate vicinity of the trailing edge will take the form shown in Fig. 2(c). (Fortunately the dc current through the connecting resistance is small so that the IR drop is not significant except at very high discharging rates.) A comparison of Figs. 2(b) and 2(c) shows that the region of high dc field at the tip of the discharge pin coincides with the RF coupling field minimum. Since the discharge occurs from the points of the needles in the general direction of the dc field lines, discharge current flows at approximately right angles to the reciprocal RF field lines. The discharge is thus orthogonally decoupled, as well as being decoupled by virtue of the minimum of reciprocal field. Finally, if very sharp points are used, the amplitudes of the individual current pulses are small [13], [14], affording a reduced noise content in the discharged current. Hence, all three of the noise reduction methods are employed, although the majority of the noise reduction results from the decoupling techniques. Laboratory tests indicated that noise reductions exceeding 35 db were possible with this design. (Residual noise in the instrumentation used for these measurements did not permit lower noise measurements.)

Because it is an integral part of the airfoil trailing edge, the flush-mounted discharger is rather expensive to in-

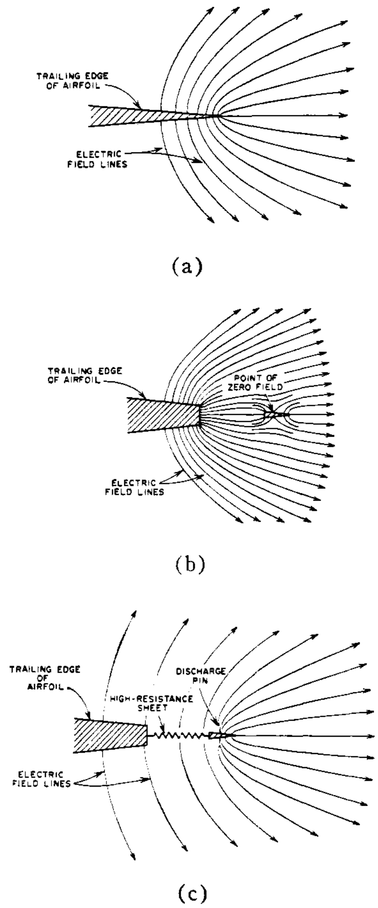

Fig. 2—(a) Electric-field configuration at trailing edge of airfoil; (b) RF coupling field configuration about airfoil with isolated edge; (c) Static field configuration about flush decoupled discharger.

stall on a finished aircraft. Also, the flush discharger has a rather high corona-threshold potential. The same principle can be incorporated in other forms of dischargers, however [14], [16]. It is apparent that the isolated conductor shown in Fig. 2 need not be continuous along the trailing edge. The arguments used in describing the decoupling mechanisms in the flush discharger apply equally well if the discharge pins in Fig. 2(c) are mounted in individual conductors attached to the aircraft surface by rods of high-resistance material. These rods may be attached at suitable intervals along the trailing edges of the airfoils.

A rod protruding aft from the trailing edge of the wing will tend to concentrate the static fields in this region, so that the corona threshold of a discharger of this type should be much below that of the trailing edge to which it is attached. The cost of fabricating, installing and maintaining rod-shaped decoupled dischargers on an aircraft should be much lower than the cost of a flush discharger installation.

The final design developed for the rod-shaped dischargers—hereafter called Type A ortho-decoupled dischargers—is illustrated in Fig. 3. Instead of being mounted in a conductor at the end of the high-resistance rod, the discharging pin was mounted directly in the rod

Fig. 3—Type A ortho-decoupled discharger mounts parallel to windstream.

itself at the position of minimum coupling near the end of the rod. The aft end of the rod is hemispherically rounded and coated with a dielectric to prevent corona from occurring at the tip where the coupling is relatively high. The rod fits into a metal socket on the mounting base which protrudes aft of the trailing edge and serves as a lightning diverter, thus tending to protect the trailing edge.

To determine optimum pin location and to investigate the degree of noise reduction to be expected, the magnitude of the coupling as a function of position along the rod was calculated [14], [16] by computing the radial field near the end of a high-resistance rod attached to a conducting sheet immersed in an RF field. The results of this calculation are shown in Fig. 4, for three values of a parameter γ, which depends on the discharger length and resistance, and on the frequency. The advantage of locating the pin somewhat forward of the end of the rod is apparent from the rapid increase in coupling near the end. The location of the region of minimum coupling along the rod was verified in the laboratory using the spark-discharge noise source probe and airfoil mock-up discussed in connection with the coupling and noise measurements described in [1].

For a typical discharger rod (at $f=1.0$ Mc) mounted on the trailing edge of an airfoil, the coupling field at the end of a discharge pin located at the point of minimum coupling on the rod is 55.6 db below the field at the end of the same pin mounted directly on the trailing edge of the airfoil [14], [16]. Laboratory measurements indicate that a given current discharged from pins with a tip radius not exceeding 0.0005 inch produces from 6 to 11 db less noise than the same current discharged directly from a typical airfoil trailing edge. (The amplitude of a corona current pulse is proportional to the radius of the discharge point, and for a given average current, the rms noise generated by a signal consisting of small pulses with high PRF is smaller than the rms noise of a signal composed of large pulses with low PRF.) Thus at 1 Mc a typical decoupled discharger installation should theoretically result in a corona noise reduction of at least 61.6 db. (Fig. 4 indicates that at lower frequencies the noise reduction will be somewhat less.) Flight test data obtained on the Boeing 707 prototype aircraft [14], [16] indicated that the noise reduction afforded by the dischargers was at least 50 db at a frequency of 500 kc. Laboratory measurements [16] indicate that 60 db noise reductions are obtainable in practice.

Service tests of the decoupled dischargers [16] indicated very little deterioration in either their me-

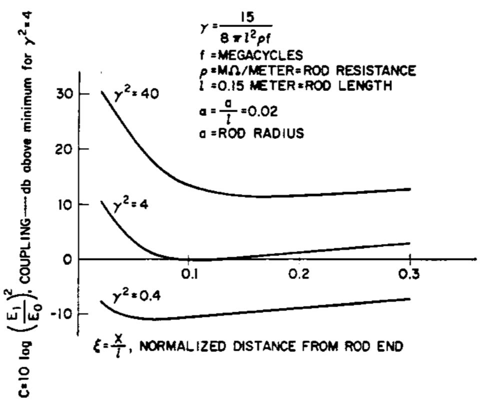

Fig. 4—Discharger noise decoupling. The coupling data have been normalized to the value of the minimum coupling for $\gamma^2=4$. The condition $\gamma^2=4$ describes, at a frequency of 0.1 Mc, the dischargers used in the flight tests for which $l=6$ inch$\simeq$0.15 meter, $a=\frac{1}{8}$-inch 0.03 meter, and $\rho=133$ megohms per meter.

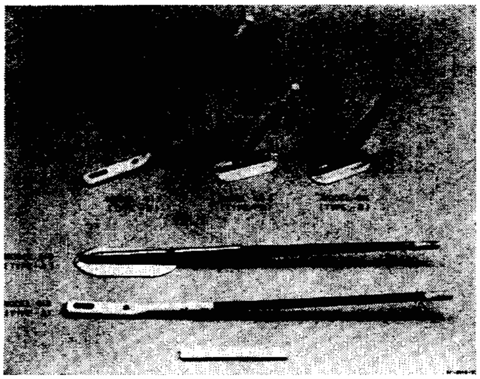

Fig. 5—Production models of type-A and type-B dischargers.

chanical or electrical characteristics after as much as 1000 flight hours. Discharger pins gradually became dulled, but the dulling had virtually no effect upon the discharging capability. Dulling of its pins increased the noise produced by a discharger; however, because most of the noise reduction results from decoupling, the dischargers were found to be effective even with dull pins. Although several of the dischargers had badly dulled or "fish-hooked" pins, and a few had one pin broken off entirely, all provided at least 30 db of noise reduction. The average noise reduction after 1000 flight hours was over 35 db (with additional development it should be possible to reduce the rate of deterioration). Thus unless the discharger is obviously damaged (pins broken off, resistive paint eroded or peeled, struck by lightning) or unless the rod resistance is too low, the discharger is probably providing at least 35 to 40 db of noise reduction.

Production versions of the retrofit decoupled discharger are shown in Fig. 5. The Type-B dischargers shown in the figure are designed to mount on the airfoil tip caps roughly at right angles to the windstream. Dischargers are required there because the vortices generated at the airfoil tips produce localized pressure reduction that reduce the corona threshold enough to permit discharges from sections of relatively large radius. The Type-B dischargers produce a column of space charge along the wing tip, which reduces the dc field there and prevents discharges from the wing tip itself.

Given a discharger capable of reducing corona noise by 50 to 60 db, it is next necessary to consider the problem of devising discharger installations such that all of the corona discharge current leaves via the dischargers. The best discharger is of no value if non-decoupled discharges occur from the airframe. The corona threshold potential of the discharger must obviously be lower than the threshold potential of any part of the airframe. Flight-test measurements on the Boeing 707 prototype indicated that, at 30,000 feet, the outboard tips of the trailing edges of the wings reached threshold at an aircraft potential of 80 kv. At the same altitude the threshold potential of a Type-A decoupled discharger mounted near one wing tip was only 8 kv. Thus the Type-A discharger will discharge large currents before any other point on the aircraft reaches corona threshold. Although a low discharger threshold potential is essential, it does not guarantee that all of the current will leave from the dischargers, since the current leaving from even a zero-threshold discharger is limited by the shielding effect of the column of space charge produced by the discharge.

In general, a wing tip discharger will discharge more current than one farther inboard because the field about the tip is more intense. Also an isolated discharger on an airfoil trailing edge will discharge more current than if a second discharger were next to it, because the space charge from the second discharge would have a shielding effect on the first. Thus, we seek an optimum distribution for several dischargers, where they are far enough apart that discharge capability is not severely limited by mutual shielding effects, and yet not so far apart that the inboard dischargers must be placed in the low-field regions. Since attempting to determine an optimum discharger arrangement experimentally on a flight-test aircraft would require far too much flight time, a technique was devised to permit studying discharger currents in the laboratory [14], [16].

Conducting rods extending aft along the windstream lines were attached to the trailing edges of the airfoils on a charged scale model of the flight-test aircraft to simulate the presence of the dischargers and their columns of space charge. The field intensity on the surface of each rod was measured, and used to calculate the current leaving that discharger in flight.[2] The validity of this technique is demonstrated when the individual discharger currents predicted from laboratory measurements are compared (Fig. 6) to the measured discharger

[2] Field measurements were made using charge separation techniques developed by Bolljahn in connection with the study of low frequency antennas [17]. Additional details of this technique are given in [14] and [16].

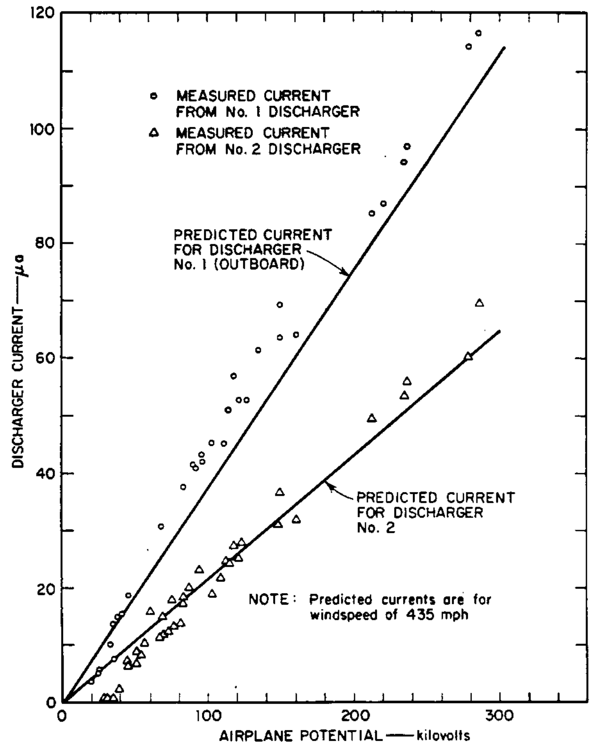

Fig. 6—Comparison of predicted and measured currents from wing trailing-edge dischargers.

currents read from three widely separated regions of the flight record obtained during one flight of the 707 test aircraft.

To find out how discharger spacing influences discharge current, six model dischargers were uniformly spaced along the trailing edge of the wing of a KC-135 model, and the total current discharged by these six dischargers was determined for several spacings. The results indicate that the maximum current for a uniform spacing is obtained when the dischargers are approximately 24 inches apart. However, because the curve is quite flat in the region of the maximum, increasing or decreasing the spacing by a factor of two does not appreciably reduce the total current discharged.

Several nonuniform spacings were investigated, in which the dischargers were placed close together in the high field regions near the outboard tip and further apart inboard from the tip. These nonuniform spacings appeared to offer no increase in the total current discharged by a given number of dischargers, although currents discharged by individual dischargers in the array varied considerably. The fact that the total current is relatively independent of spacing may be explained by observing that, within the range of spacings investigated, changes in mutual shielding almost exactly nullify changes in field intensity as spacing is varied.

The effect of changing the number of dischargers in an installation was investigated by determining the total current discharged when from 4 to 14 dischargers spaced 18 inches apart are installed on an airfoil. The results indicate that, after the first few dischargers are installed, each additional discharger provides an equal increment of discharging capacity. This result together with the results of the spacing tests indicate that simply installing additional dischargers makes it possible to increase the discharging capability of an installation to any reasonable value.

While the uniform spacing appears to be adequate to discharge maximum current at a given aircraft potential, an optimum distribution of dischargers requires also that the threshold potential for non-decoupled discharges be maximized. For turbojet aircraft, this implies maximum corona threshold potential of points along the trailing edge between the dischargers subject to the condition that the discharger current also remain maximized.

Using charge separation techniques [14], [16], it is possible to determine the field E_d at a point d units forward of the trailing edge (d was taken to be $\frac{1}{3}$ inch) for which the trailing edge goes into corona. The threshold potentials of points along the trailing edge of the KC-135 wing were determined by making field measurements at a corresponding distance forward of the trailing edge on a model of the aircraft wing energized to a known potential. Measurements (Fig. 7) were made for the case of no discharge current and for the case of current leaving dischargers attached to the trailing edge. (The dischargers and the columns of space charge emanating from them in flight were simulated by conducting rods attached to the trailing edge as in the experiments to determine discharger currents.) The effect of the space charge in increasing corona thresholds is evident in Fig. 7. Since the total current is not critically dependent upon spacing, the airfoil corona threshold potential is most easily maximized by decreasing the spacing of the outboard dischargers to produce a dense column of space charge. Indeed, because the most critical region is the few inches of trailing edge at the outboard tip of the airfoil, only the spacing of the two dischargers furthest outboard need be considered. Although the threshold potential of the trailing edge increases as the spacing decreases, decreasing the spacing below about 12 inches appears to offer little advantage because at this spacing the threshold potential of the trailing edge is as high as, or perhaps higher than, some other points on the aircraft such as the airfoil tips or points inboard of the dischargers on the wing. Thus, a distribution in which the two furthest outboard dischargers are 12 to 18 inches apart and the rest are about 24 inches apart is very nearly optimum.

For the discharger installation flight-tested in the 707 prototype (a total of 29 dischargers with a spacing of 15 inches), laboratory measurements predicted that at 15,000 feet, high-field points on the wing just inboard of the innermost discharger would reach corona threshold with a total aircraft charging current of approximately 3.5 ma. No noise was observed during the flight

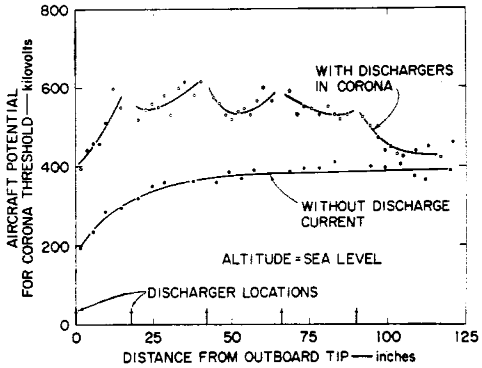

Fig. 7—Threshold potentials of points along trailing edge of wing on KC-135.

tests in which the maximum charging current measured was slightly over 3 ma. Thus the discharger complement used in the flight tests was adequate to discharge without noise the highest charging currents encountered in the tests, but probably would not handle currents much greater than these. Charging currents as high as 4 ma have been measured on a DC-8 equipped with 36 dischargers without noise in the receiving systems. Charging data obtained from 600 hours of recording on a 707 operated by Qantas Empire Airways indicate that the charging current exceeded 4 ma only 0.002 per cent of the total flight time. Thus the installation used on the 707 and DC-8 should be effective in eliminating corona noise during 99.998 per cent of the time.

C. Biased Decoupled Dischargers

Although the decoupled dischargers discussed will discharge an aircraft without generating noise in its receiving systems, the airplane potential must be several thousand volts before discharging occurs. For certain special applications such as the study of atmospheric electric fields it is often necessary that the airplane potential be held at a predetermined potential, including zero. When helicopters hover to pick up cargo, it would be desirable to maintain the aircraft at zero potential to minimize the shock hazard to ground personnel and reduce the likelihood of igniting flammables. The device used to adjust the aircraft potential should not generate interference in the receiving systems.

A device fulfilling these requirements is readily evolved from the flush decoupled discharger of Fig. 2(c). The connection between the high-resistance sheet and the airframe may be broken and a high-voltage power supply interposed between the sheet and the airframe. Since this modification in no way alters the RF fields, the noise decoupling is unaffected. With the power supply activated, however, it is now possible to discharge current from the pins even when the potential of the aircraft itself is zero. Thus, the biased discharger may be used to maintain zero aircraft potential under precipitation or engine-charging conditions. In addition, if the bias supply potential is sufficiently high, it is possible to discharge current of a given polarity even when the aircraft is charged to the opposite polarity. Thus, the device may be used as an artificial charging device.

There is an upper limit on how much current can be discharged from a biased discharger. In the absence of wind, no net charge would leave the system. Ions produced by corona discharges from the pins would be directed back to the aircraft by the field existing between the isolated electrode and the airframe. In flight, the wind stream overcomes the applied electric field and carries the ions away so that charge does leave the system. If the bias potential is increased until the wind can no longer overcome the applied electric field some of the discharge current will return to the aircraft. Once this limit is reached, the discharge current can be increased only by increasing the length of the discharger transverse to the airstream, or by increasing the wind velocity.

It should be observed that when the biased discharger is used to artificially charge the aircraft, the attainable aircraft potential may exceed the bias supply potential. This is possible because the bias supply is required only to produce sufficient field at the pins to maintain the corona discharge. The work required to move the space charge away from the aircraft is supplied by the windstream. For example, at an altitude of 14,000 feet the airplane potential could be raised to a negative value of 135 kv with a positive bias-supply potential of 50 kv.

D. Some Proposed Dischargers

It will be of interest to consider various proposed discharger configurations in the light of the coupling theorem of (1). Laboratory noise measurements made to support certain of the arguments are summarized in Fig. 8.

1) *Wire Dischargers:* Various devices fabricated of small-diameter wires have been proposed as aircraft static dischargers. These devices were conceived when it was felt that discharges from the receiving antenna itself were the only important source of precipitation-static interference. Since a wire or cable protruding aft from an airfoil extremity will have a lower corona threshold potential than the airfoil extremity itself, it was reasoned that the dischargers would begin discharging at very low airplane potentials, thereby preventing corona from the antenna itself. However, [1], precipitation static noise is not generated by discharges from the antennas only; discharges at the airfoil extremities can generate severe interference in receiving systems. For this reason, it is important to consider the degree of noise reduction afforded by wire dischargers.

Laboratory data of Fig. 8(B) indicate that the noise generated by discharges from a set of needles protruding ¼-inch aft from an airfoil trailing edge produce roughly 7 db less noise than does the same current discharged from the trailing edge itself. (The reasons for this noise

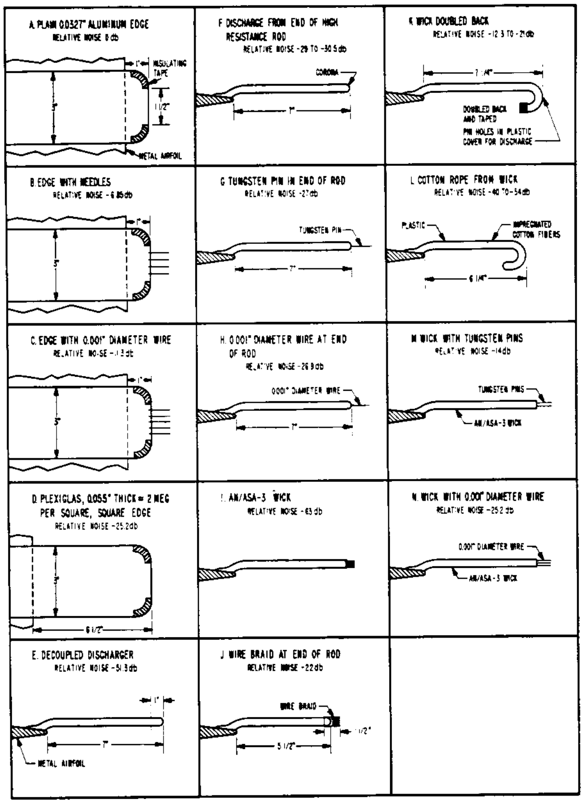

Fig. 8—Results of measurements of noise generated when a given current is discharged from a proposed discharger. Noise levels are expressed relative to the noise generated when the same current is discharged from the edge of a 0.0327 inch thick aluminum sheet simulating the trailing edge of an airfoil.

reduction were given in the discussion of the decoupled discharger.) Using carefully selected pins with a tip radius not exceeding 0.0005 inch, the noise reduction was 11 db. Similar noise reductions were observed for 0.001-inch-diameter wires, Fig. 8(C). Thus a short (fraction of an inch long) wire or needle discharger should produce a relatively insignificant noise reduction when installed on an aircraft. Increasing the length of the wire discharger to increase the dc field at its tip (thereby reducing its corona threshold potential) simultaneously increases the magnitude of the coupling field, cancelling some of the potential 6 to 11 db noise improvement occurring from the use of fine discharge points. Thus one should expect virtually no noise reduction from the use of wire dischargers.

2) *High-Resistance Rods and Sheets:* It has been suggested that discharges occurring from high-resistance coatings on sheets, rods, or ropes made of insulating material are inherently "noiseless," and that these high resistance conductors by themselves constitute satisfactory dischargers. For a sheet attached to the trailing edge of an airfoil, the noise content of the discharge current J_2 will be the same whether the discharge occurs from the trailing edge or from the sheet as long as the two have roughly the same thickness. Furthermore, the direction of J_2 will be along $\boldsymbol{E}_1$. Thus, applying (1), it is evident that noise is reduced through the use of the high resistance sheet only because the sheet is transparent at RF frequencies and the discharge is caused to occur away from the trailing edge in a region of reduced reciprocal field $\boldsymbol{E}_1$.

The degree of noise reduction can be estimated by noting that the field in the plane of a conducting sheet varies as

$$E(x) = A/\sqrt{x} \tag{2}$$

where x is distance aft of the trailing edge and A is a constant related to the amplitude of the applied voltage. The decoupling is given by

$$\frac{E_2}{E_1} = \sqrt{\frac{x_1}{x_2}}, \tag{3}$$

where E_1 is the coupling field at the airfoil trailing edge and E_2 is the coupling field at the aft edge of the high-resistance sheet. [Eq. (3) is strictly valid only if the sheet resistance is infinite. In practice the noise reduction will be lower than that indicated by the equation.] Assuming that the shape of the trailing edge may be approximated by the equipotential passing through $x_1 = 0.1$ cm and that the sheet is roughly $6\frac{1}{2}$ inches long ($x_2 = 16.5$ cm) the maximum noise reduction from (3) is -22.2 db which agrees well with the value of -25.2 db measured in the laboratory, Fig. 8(D).

To further investigate the noise generated by discharges from resistive points, the noise reduction afforded by a decoupled discharger was measured, Fig. 8(E). Next the discharge pin was removed from the rod and the discharge permitted to occur directly from the end of the rod as in Fig. 8(F). The noise generated was increased by roughly 20 db.

In a further investigation, the noise generated by an AN/ASA/3 wick discharger [Fig. 8(I)] was measured. Next, the end of the wick and roughly $\frac{1}{2}$ inch of the plastic sleeve were doubled back and covered with insulation tape, as in Fig. 8(K). Pinholes were punched in the plastic sleeving at the end of the wick to permit discharges from the high-resistance wicking inside the sleeve. Modifying the wick in this manner increased the noise it generated by 40 db or more. Thus the laboratory measurements, in agreement with (1), indicate that the use of resistive materials alone does not assure one of a low-noise discharger.

3) *High-Resistance Rod with Metal Discharge Points:* Although AN/ASA/3 wick dischargers are effective when new [Fig. 8(I)], their characteristics deteriorate rapidly in flight as the conductive material on the individual fibers at the end of the wick becomes whipped out or broken, so that conductive segments of the fibers are isolated from the rest of the wick by insulating sections. It has been suggested, therefore, that wick deterioration could be reduced by using metal discharge points at the end of the wick instead of conductively coated dielectric

fibers. Applying (4) to this case, it is evident that the noise produced by a discharge from a set of needles or wires placed at the end of a 6.5-inch-long high-resistance rod or wick should be roughly 22 db lower than the same discharge would produce if the points were mounted directly on the airfoil trailing edge. Comparison of Figs. 8(G), (M) with Fig. 8(B), and Figs. 8(H), (N) with Fig. 8(C), affirms that this is the order of noise reduction. Furthermore, comparing Figs. 8(M), (N) to Fig. 8(I), it is evident that the use of metal discharge points degrades wick performance by 35 to 40 db. A comparison of Figs. 8(E) and (G) indicates the penalty paid for locating the discharge pin at the end of the discharger rod instead of the position of minimum coupling

4) *General Observations:* Comparing Figs. 8(A) and (D) we observe that noise can indeed be reduced by relocating a given discharge (J_2 still along $\boldsymbol{E}_1$) in a region of reduced reciprocal field $\boldsymbol{E}_1$. The noise reduction achieved by simply reducing the magnitude of $\boldsymbol{E}_1$, however, does not approach the ultimate capability of a good discharger.

An interesting observation may be made upon comparing Figs. 8(F) and (G). In (F) the discharge occurs from the large radius of the tip of the rod so that J_2 consists of high amplitude pulses and is very noisy. In (G), on the other hand, the discharge occurs from a sharp pin so that J_2 consists of lower amplitude pulses and is less noisy. Thus, at first glance, one might expect (G) to be less noisy than (F). The metallic pin in the end of the rod in (G), however, concentrates the field at the end of the pin so that $\boldsymbol{E}_1$ is higher in (G) than in (F). These two effects are of comparable magnitude so that the noise in the two cases is almost the same. Thus placing fine discharge points at the end of a high-resistance rod does not, in general, result in a satisfactory discharger.

Fig. 8(I) indicates that a new wick produces a satisfactory degree of noise reduction. Figs. 8(K), (M) and (N), however, demonstrate that the noise reduction is not the result of some property of the body of the wick since (K), (M), and (N) are certainly not satisfactory dischargers. It appears, therefore, that a significant portion of the noise reduction afforded by a wick follows from the pulse-amplitude-limiting action of the high resistance and low capacitance of the individual fibers at the end of the wick. On a new wick most of the fibers are slightly conducting so that they can sustain discharges. The effective capacitance of the fiber is so low, however, that only a small amount of charge can accumulate on the fiber before the threshold field is reached at the surface. The charge transferred in one corona pulse is therefore quite small, and the result is that the noise content of the discharge J_2 is relatively low.

To further verify the observation that the thin, high-resistance conducting fibers are responsible for the degree of noise reduction obtained with a new wick, the plastic tubing was removed from a "doubled-back" wick as in Fig. 8(L) permitting some of the conducting cotton fibers to protrude from the body of the wicking. Since only a few fibers protruded, the noise varied as the conductive material burned off the end of one fiber and the discharge shifted to another fiber. The noise reduction obtained with configuration (L) was roughly 30 db more than that obtained in (K). Thus (L) would be an acceptable discharger until the protruding fibers burned off and the noise reverted to that obtained in (K).

All of this shows that the main difficulty associated with the use of wick dischargers is their reliance on fragile resistively impregnated fibers for noise reduction. With use, the resistive impregnation washes out or is whipped out by the airstream and many of the fibers become insulating (or possibly partially insulating), so that conductive segments of the fibers are isolated from the remainder of the wick by insulating sections. These insulating or isolated fibers not only cannot sustain a discharge current but, since they acquire a static charge, they behave somewhat as a space charge and tend to prevent discharges from the conducting fibers. Trimming the wicks sometimes restores their performance, since it removes the insulating fibers at the tip of the discharger and exposes some of the inner fibers that have not been washed out. However, since there is no visible difference between conducting and nonconducting fibers, one is still faced with deciding whether to trim the wick or replace it.

III. Antennas

A. General

Although decoupled dischargers can usually give the required degree of precipitation-static noise reduction, certain vehicles may not lend themselves to discharger installation. For this reason, it is wise to consider other techniques for eliminating precipitation static. Since antenna design and placement influence the coupling between the noise source and receiver [1], it will be worthwhile to consider antenna designs which may be used to reduce this coupling to minimize precipitation-static interference.

B. Comparison of Loop and Dipole

Assume that, as in Fig. 9, a loop and a dipole are both installed at a distance z from the nose of the aircraft fuselage. A noise source at some other extremity excites a noise current I_n on the fuselage. The current distribution on the fuselage is given by

$$I_n(z) = I_{n0}f(z). \tag{4}$$

If the cross-sectional area of the fuselage is uniform throughout its length, the current will have approximately a triangular distribution, or $f(z) = z$.

The magnitude of the open-circuit voltage induced in the loop antenna is proportional to the magnitude of the magnetic field at the position of the loop, which in

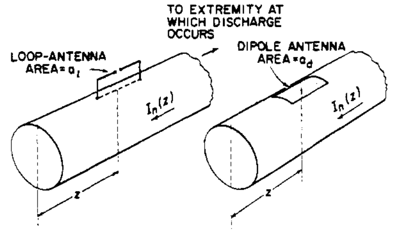

Fig. 9—Loop and dipole installed on airplane member.

turn is proportional to the noise current flowing in the fuselage. The short-circuit current induced in a dipole, on the other hand, is proportional to the surface density of charge produced on the fuselage by the flow of noise current. Thus the loop and dipole should have a different susceptibility to precipitation static interference. For the loop antenna it can be shown [14] that the equivalent noise field produced by the noise current flowing in the fuselage is

$$E_{nl} = \frac{\eta_0 \rho}{\gamma_s} I_{n0} f(z), \tag{5}$$

and for the dipole antenna the equivalent noise field is

$$E_{nd} = \frac{\rho}{s\epsilon_0 \gamma \omega} I_{n0} f'(z), \tag{6}$$

where

s = peripheral distance around fuselage,
ρ = a factor indicating relative current concentration at the point on the periphery where the antenna is located,
γ = the curvature factor giving the field concentration due to the presence of the conducting cylinder,
η_0 = the intrinsic impedance of free space,
ϵ_0 = dielectric constant of free space,
ω = radian frequency.

For the triangular current distribution, (5) and (6) become, respectively,

$$E_{nl} = \frac{\eta_0 \rho}{\gamma s} I_{n0} z \tag{7}$$

and

$$E_{nd} = \frac{\rho}{s\epsilon_0 \gamma \omega} I_{n0}. \tag{8}$$

It is evident from (8) that the dipole noise field is independent of position along the cylinder, whereas (7) indicates that the loop noise field increases with increasing distance from the end of the cylinder. Thus, the signal to precipitation-static noise ratio of a loop is optimized by mounting the loop antenna as close as possible to the nose of the aircraft.

Another interesting comparison between the characteristics of the loop and dipole may be made by noting from (8) that for a given noise current the equivalent noise field of the dipole varies inversely with frequency. Thus, although a given noise current may not produce serious interference at high frequencies, it may still disable communication and navigation equipment at the low frequencies. In the loop antenna, however, (7) indicates that the noise field is independent of frequency. This is undoubtedly the reason for the frequently observed superiority of a shielded loop over a dipole for low-frequency reception under precipitation static conditions.

Combining (5) and (6), we can write the ratio of the noise fields induced in the loop and the dipole, as follows:

$$\frac{E_{nl}}{E_{nd}} = \eta_0 \epsilon_0 \omega \frac{f(z)}{f'(z)} = \frac{\omega}{c} \frac{f(z)}{f'(z)}, \tag{9}$$

where $c = 3 \times 10^8$ meters/sec. For the triangular current distribution, (9) becomes

$$\frac{E_{nl}}{E_{nd}} = \frac{\omega}{c} z. \tag{10}$$

This equation indicates that the superiority of the loop over the dipole increases as the frequency and distance from the end of the cylinder decrease.

C. Decoupled Antennas

It is evident that a good position for a loop is at the end of any member from which discharges do not occur (such as the nose of the fuselage). Often, however, a loop cannot be mounted at the very nose of the aircraft. In this case, it is worth noting that (5) gives the maximum noise coupled into a loop, and that the equation is valid only if the loop is oriented as in Fig. 9, with its axis at right angles to the cylinder axis. If the loop is rotated 90 degrees until its axis parallels the axis of the cylinder, there will be no coupling between the loop and the noise currents on the cylinder, and the equivalent noise field will be very low even if the loop is aft of the nose. It was determined experimentally [14] that rotating the loop in this manner results in a decoupling of roughly 25 db. Orienting a loop with its axis parallel with the axis of the fuselage of the aircraft, however, produces a null in the radiation pattern in the fore and aft direction. This objection may be overcome by using two loops mounted on orthogonal members of the aircraft with the axis of each loop parallelling the axis of the member on which it is mounted (one loop on the fuselage and one loop on a wing, for example). Each loop is decoupled from the noise currents on its airplane member, but since the two loops are at right angles, pattern coverage is omniazimuthal.

A noise-cancelling scheme may be used to decouple dipole antennas from precipitation-static interference. Consider two dipole antennas mounted at the same fuselage station—one on the top centerline and the other on the bottom centerline. If a noise current is induced in the fuselage by a discharge from an extremity, the charge density resulting from this noise current will in general be the same at the lower and upper antenna locations. Furthermore, the charge variation at the two locations will be in phase. Thus, equal, in-phase, noise currents will be generated in the two antennas. A vertically polarized signal, on the other hand, will induce equal signal currents 180 degrees out of phase in the two antennas. If the outputs from the two antennas are fed to a balanced input transformer, the noise currents will cancel and the signal currents will add. The radiation pattern of this antenna combination is omniazimuthal to vertically polarized signals, with negligible response to horizontally polarized signals.

In the experimental investigation of this decoupling technique, the two antennas were balanced by variable attenuators and a line stretcher in the lines to the antennas. It was found possible to obtain at least 25 db of decoupling from noise generated at any aircraft extremity. For these tests the antennas were located on the fuselage two-thirds of the way from the nose to the leading edge of the wing.

Essentially the same noise cancelling scheme is possible if the dipoles are replaced by loops. Each loop should be oriented with its axis athwartship. If the fuselage is symmetrical, the magnitudes of the noise signals induced in each of the two antennas will be equal, and the loops can be so connected to the receiver that the noise signals cancel and the desired received signals add. The resulting antenna system will have a normal loop radiation pattern with a null athwartships of the aircraft.

Noise-cancelling schemes using either loops or dipoles will work perfectly only if the aircraft is symmetrical about a horizontal plane, if the balanced antennas are symmetrically located with respect to this plane and if all corona-noise sources lie in the plane of symmetry. In this case an adjustment of balance which results in minimum noise from a source at one extremity will be optimum also for discharges from the other extremities. In actual aircraft these conditions are only approximated. Experiment indicates, however, that in the quasi-static frequency range a balance can be obtained that results in an over-all reduction of noise from sources at all extremities of greater than 25 db.

Flight-test verification of decoupled antenna performance was not attempted, primarily because the decoupled discharger tests were so successful.

IV. Ionized Engine Exhaust Discharger

One approach to the reduction of noise produced in discharging an aircraft is to reduce the noise generated by the discharging noise source. An obvious noiseless discharging technique is the use of a region of ionized air to accomplish the discharging. The possibility of using the ionized jet engine exhaust immediately presented itself. It was felt that it might be possible, by placing a negatively biased rod in the engine exhaust, to extract positive ions and use the biased rod as a discharger. Tests were conducted using a J57 jet engine mounted in a ground test stand. In these tests a 24-inch-long steel rod connected to a variable high-voltage supply was placed along the engine axis immediately aft of the engine exhaust cone. It was found that with maximum throttle setting on the engine and with 10 kv applied to the rod, the current was roughly 7 microamperes, regardless of the polarity of the applied voltage. These results indicated that the conductivity of the exhaust gases is too low to permit their use as a precipitation static discharger since discharging normal currents would require either prohibitively high voltage or a very large total electrode area immersed in the exhaust. For this reason, no further effort was made to test this method of aircraft discharging.

V. Receiver Circuitry

The problem of reducing precipitation static can also be attacked at the receiver terminals. Whereas other methods attempt to reduce the noise coupled into the antenna, the blanker attempts to improve the signal-to-noise ratio by electronic methods within the receiver.

In principle, the blanker is an ideal switch which is placed ahead of the receiver to completely suppress both signal and noise by shorting the receiver input whenever a noise pulse appears. This blanking period must be long enough that a significant portion of the high-energy pulse will be suppressed.

As the length of the blanking period increases, the signal power at the output of the receiver will go down. Indeed, not only does the signal power decrease but the noise due to blanker switching-action increases. Thus it is of primary importance to make the blanking period as short as possible. It follows that the blanker must be located ahead of any filtering in the system, otherwise the noise pulses would be very much extended in time by the narrow-band filters.

The switching action of the blanker will introduce power at signal frequencies which results from the pulse modulation of the desired signal carrier and of any other carriers or signals accepted by the receiver front-end. Because this power provides no information it must be considered as noise. The requirement that no filtering precede the blanker permits the receiver front-end to accept signals over a wide frequency band, thereby aggravating the problem of noise produced in this manner. It is important to note that some filtering could be accomplished before the blanker; however, the Q of the circuits must be so low that very little benefit is realized because it is the carriers near the signal carrier that contribute most heavily.

An analysis has been carried out for an ideal blanker followed by an ideal receiver [8]. The ideal blanker characteristics were assumed to be such that, once a blanking period is initiated by a pulse it will last for a time t if no other pulses arrive during this period. Otherwise, the period will be extended. It is apparent that the blanking period will continue until two pulses are separated by more than t in time. Thus, every pulse creates a gate of length t after it, and consequently all the tails of the noise pulses will be eliminated.

When a typical input to a blanker is considered, consisting of an amplitude-modulated carrier plus a number of outside carriers, it is found that each input term will contribute discrete and continuous spectra in the output of the blanker. The band-pass and low-pass filters of the receiver will eliminate all discrete signals except the modulation of interest. However, some noise from every term will pass through the filters and contribute to the output.

There is no question that a blanker can provide considerable improvement when there are only a few very-high-energy pulses to contend with. However, the number of precipitation-static noise pulses, even in relatively light precipitation, is very high. In addition, corona noise pulses are lengthened by aircraft resonances prior to their arrival at the receiver terminals [8]. Both of these facts lower the effectiveness of the blanker. The performance of a blanker has been compared with that of decoupled dischargers in reducing corona noise interference on a Boeing 707 aircraft under a precipitation-static condition where the total discharge current was 1 milliampere [8]. The decoupling provided by the dischargers was assumed to be 50 db while the blanker was assumed to be the ideal blanker described. Initially it was assumed that no outside carriers were present. Even so, the blanker was found to be inferior to the dischargers in suppressing noise. The analysis indicated that a single outside carrier in the frequency vicinity of the carrier of interest, having an amplitude only 4.6 times that of the wanted carrier, will reduce the signal-to-noise ratio at the output by a factor of 10.

Another important effect of using a blanker is the serious loss of sensitivity which results from the fact that no tuning can be accomplished at the antenna terminals. A tuned blanker has been proposed, which theoretically will have a high-Q input until a noise pulse arrives, when the circuit Q will be drastically reduced to prevent ringing. After the energy of the pulse has been dissipated, the circuit is again opened up. Not only does it take time to dissipate the energy but, more important, the recovery time of the tuned circuit is so long that, under conditions of precipitation static, the blanker will hardly ever attain an unblanked state. Although the tuned blanker might reduce the outside carrier contribution of noise, the signal-to-noise ratio, even neglecting outside carriers, is worse than that for the untuned blanker.

Finally, the many practical limitations in a theoretically satisfactory blanker are very severe. For example, in presently available designs, a minimum blanking period of 6 μsec. is considered good. With a total aircraft discharge current of 1 ma, the average time separation of pulses is only 1 μsec. Consequently, if the pulses were uniformly spaced, the receiver would remain permanently blanked with a discharge current of one-sixth this great. The fact that the pulses are randomly spaced results in the existence of some periods during which the receiver accepts signal even with 1 ma discharge current, but it is evident that little improvement in signal-to-noise ratio can be expected—even in the absence of the noise generated by the presence of outside signals.

In view of the poor performance predicted for an ideal blanker under precipitation charging conditions, together with the fact that its use requires interposing a complex active circuit system between the antenna and the receiver, it was felt that other techniques offered much more promise. For this reason the blanker was not tested either in the laboratory or in flight.

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Conservative Coupling Between Modes of Propagation—a Tabular Summary*

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***Summary*—There are four distinct ways in which two modes of propagation can be coupled conservatively, *i.e.*, coupled so that the mode amplitudes satisfy either a power conservation law or a Manley-Rowe relation. The type of coupling that results in any particular case depends upon the relative parities of the modes, the relative directions of the group velocities and, in the case of parametric coupling, the relative signs of the frequencies of the two modes. Each of these four types of coupling results in a distinct and characteristic type of behavior.**

This paper presents a set of tables that summarize the principal characteristics of the four types for both direct and parametric coupling.

Introduction

Since the publication of the initial paper by Pierce[1] in 1954 and the subsequent application of the technique to parametric systems by Tien[2] in 1958, a considerable body of material has been published on the theory of coupled modes of propagation.[3] This paper does not propose to add anything new to the substance of that body, but rather to add to the form by tabulating explicitly in a concise, and hopefully useful, form the principal characteristics of pairs of modes that are coupled conservatively.

In coupled-mode theory, the behavior of a coupled system is described in terms of the normal modes of the uncoupled system. The equation that characterizes the behavior of coupled modes of propagation takes the form

$$\frac{\partial a}{\partial z} = -iRa \tag{1}$$

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R. W. Gould and C. C. Johnson, "Coupled mode theory of electron beam parametric amplification," *J. Appl. Phys.*, vol. 32, pp. 248–258; February, 1961.

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See also the papers listed under footnote 4.

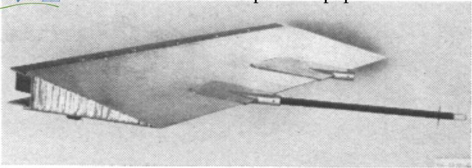

Fig. 3—Type A ortho-decoupled discharger mounts parallel to windstream.

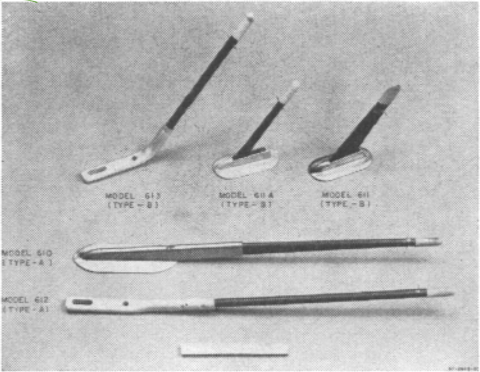

Fig. 5—Production models of type-A and type-B dischargers.