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DESIGN OF CIRCUITS FOR COUPLING A DIRECTION FINDER TO A 4-ELEMENT AND 8-ELEMENT ADCOCK ANTENNA

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ABSTRACT

An experimental method of determining the parameters of antenna coupling circuits is presented, with particular application to a twin-channel direction-finding receiver fed from a 4-element and 8-element Adcock antenna. The measurement technique is straightforward and provides a direct indication of efficiency and matching. The results of a gain comparison between the two antenna systems emphasize the importance of these coupling circuits on overall sensitivity.

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DESIGN OF CIRCUITS FOR COUPLING A DIRECTION FINDER TO A 4-ELEMENT AND 8-ELEMENT ADCOCK ANTENNA

- N. Burtnyk -

INTRODUCTION

The problem of coupling an antenna to a receiver over a wide bandwidth is generally considered to be difficult. If the antenna has several resonances in this bandwidth, the large variation of antenna impedance at the series and parallel resonances causes a transfer of large reactive components of impedance into the coupled circuits. This difficulty can generally be overcome by tuning the antenna. However, in a system such as an Adcock feeding a twin-channel receiver the antenna cannot be easily tuned over its frequency range and one must deal with these primary circuit resonances directly. The design is also more critical than with a single-channel receiver where sensitivity is the main criterion. In a twin-channel receiving system, the phase and amplitude balance between the two channels is of utmost importance, and hence the phase shifts and detuning effects that accompany the transfer of large reactive components at the primary circuit resonances must be very carefully controlled.

The parameters of the input circuits can be determined approximately from the measured impedance curves of the antenna and the input impedance of the receiver, but in practice there are several uncertain quantities which must be dealt with experimentally. These calculations, however, serve as a very useful guide in a preliminary design, and the final design can be critically controlled by the results of the following tests and measurements.

PRELIMINARY DESIGN USING ANTENNA IMPEDANCE CURVES

A typical set of antenna impedance curves is shown in Fig. 1. The upper curves give the series R and X components of the impedance of two opposite elements of a 4-element Adcock antenna. The lower curves are a conversion to effective parallel components of the impedance, and give a direct indication of the loading applied across the primary coil for the calculation of circuit resonances. By drawing the inductance curve of the primary coil for each band, as shown, the frequencies at which primary circuit resonances will occur will be given by the intersection of these curves with the antenna reactance curves. Some of the resonances will be negligible because of the heavy damping imposed by the resistive components (as at 6.3 mc/s in Fig. 1). Others will produce a high degree of overcoupling between the primary and secondary circuits, resulting in excessive detuning or transfer inefficiency over parts of the band. There will also be a downward shift in these resonances effected by the self-capacity of the primary coil and the stray capacities at the receiver input. By manipulating the size of coil for a given frequency band, primary circuit resonances can be controlled to such an extent that an acceptable

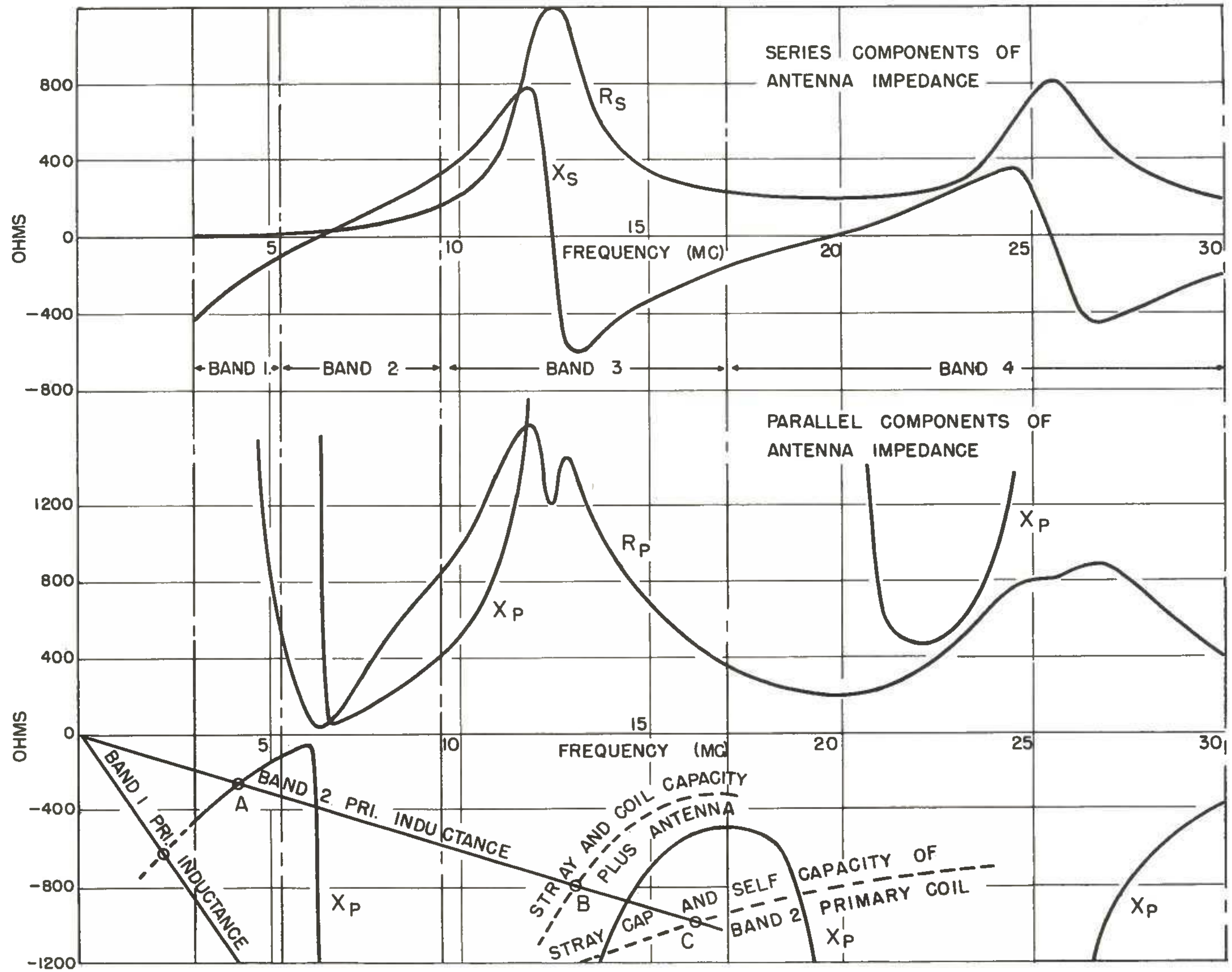

FIG. 1. MEASURED IMPEDANCE CURVES OF A 4-ELEMENT ADCOCK ANTENNA

preliminary design can be achieved. This is especially so if there is no necessity for a compromise to be made. If, however, the antenna spacing and/or frequency bands are such that series resonances cannot be completely shifted out of the band by a choice of primary coil inductance, other methods must be used. An extension of the length of antenna feeders can be used to lower the frequency of a primary resonance, or resistive damping may be used to reduce the detuning effects at such resonances. Furthermore, the actual amounts of detuning produced and the efficiency of transfer of any given input coupling circuit depend directly on the coefficient of coupling and this must be determined and controlled by some means.

The design of the secondary coil is generally relatively straightforward. In the usual case of tuned RF systems with capacitive tuning, the size of the secondary coil can be quite accurately determined from the value of tuning capacity and an estimate of the amount of negative inductance transferred from the primary. This will produce a good preliminary design from which the final design can be derived.

METHOD OF MEASUREMENT

The instrument used for the following measurements was a Boonton Radio Corporation Type 250-A RX meter. It is a completely self-contained instrument consisting of an oscillator, an RF bridge, and a detector for measuring the equivalent parallel resistance and parallel reactance of a two-terminal network. The range of resistance measurements is from 15 ohms to infinity, capacity measurements from zero to 20 pf, and inductance measurements from zero to 100 pf of effective tuning capacity. The range of inductance measurements can be extended by the addition of external capacity across the measuring terminals. If such external components are used they should be wrapped in foil which is connected to the grounded end of the capacitors to prevent any variation in capacity due to movement of the components during the measurements.

The method of measurement is as follows. The secondary winding of the input coupling transformer is connected across the terminals of the RX meter and measurements of parallel resistance (R_p) and effective parallel capacity (C_p) required to tune the coil are made with the primary coil open-circuited, and also with the primary coil loaded by the antenna impedance. Care must be taken that the stray capacities of the coil terminal assemblies in the test setup are similar to those existing in the receiver for which the input coils are being designed. Also, any shield cans for the coils and flexible contact strips used in the receiver, as in the case of turret band-switched receivers, must be incorporated in the measurement setup to realize practical conditions.

The values of R_p give a measure of the secondary circuit Q for loaded and unloaded conditions, indicating the relative efficiency of coupling, while the values of C_p when plotted against $1/f^2$ show the variation of total effective secondary inductance across the frequency band. For the unloaded condition, there is generally a linear relationship between C_p and $1/f^2$, indicating a transfer of a constant amount of negative inductance from the primary to the secondary, while for the loaded condition there will usually be a deviation from this relationship due to a change in the amount of reactance transferred, especially in the vicinity of the primary circuit series resonant frequencies. This will result in detuning of the secondary circuit and, because these secondary circuits must be tracked in a twin-channel receiver, it represents the main problem that is encountered in the design of these coupling circuits.

DESIGN CRITERION

A series of tests and measurements were made on the coupling circuits for Band 1 of the AN/GRD-501 receiver fed by the 4-element Adcock antenna referred to in Fig. 1. Several different designs were produced, each of which met the requirements set by the limits of detuning and bandwidth. These included designs in which primary circuit resonances were located below, above, and inside the band. The effects of damping resonances in the band were also investigated. Sensitivity comparison tests were then made, and the following design rules were established.

1) Primary circuit series resonances should be shifted out of the band, if possible. Failing this, the coefficient of coupling must be reduced considerably to limit detuning to an acceptable amount; this results in a high degree of inefficiency away from the resonance. The other alternative, of damping the resonance, also results in very low coupling efficiency across most of the band. In general, a resonance in the band should be avoided.

2) If there is a choice of shifting a series resonance above or below the band, the latter is preferable as it apparently results in greater overall efficiency. Also, the desired value of coupling coefficient is usually more easily achieved with the higher inductance primary, especially if the construction is governed by shielding requirements to prevent stray capacitive coupling.

3) Antenna parallel resonances may be left in the band without a detuning effect, as the impedances are too high to load the primary coil appreciably.

4) The resistance of the primary coil should be minimized, especially when the antenna impedance has a low series resistance component.

5) The initial Q of the secondary coil should be as high as practical.

6) Stray capacities at the receiver input should be minimized, as their effect is to crowd the higher antenna resonances by shifting them downwards in frequency.

OTHER FACTORS AFFECTING THE DESIGN

The electrical design of these circuits is often restricted to some degree by their physical construction to suit the particular requirements of shape and size.

In the specific receiver system referred to in this article, balanced to unbalanced operation of the input circuit was required. For this purpose a Faraday screen capable of good push-push rejection up to 30 mc/s was incorporated in the design. Band-switching was accomplished by means of turrets, which imposed further restrictions on the shape and size of the coils. Ease of maintenance, performance stability, and component standardization requirements further contributed to the determination of the final design.

Several different Faraday screen designs using the specified turret coil cans and coil forms were produced, the type shown in Fig. 2 proving the most satisfactory from the standpoints of construction simplicity and electrical performance. The screen consists of a cylinder of copper foil with a single slot across it opposite the coil terminals. The order of rejection that was obtained was about 40 db at 30 mc/s.

Other types of screens tested took the form of covered or uncovered bobbins of silver-plated brass in which the primary coils were wound. They were generally difficult to construct and the performance characteristics varied considerably. Since these assemblies were placed on the coil form adjacent to the secondary coil, the maximum coupling coefficients obtainable were insufficient. Furthermore, large primary inductances, as required in Band 1, became impractical as the length of the bobbin became excessively long or the self-capacity of the coil became intolerable.

SAMPLE DESIGN

A typical set of measurements is shown in Fig. 3. The data applies to the design of a coupling circuit for Band 2 of receiver AN/GRD-501 fed by the 4-element Adcock antenna. The frequency range of the band is from 5.3 to 9.5 mc/s.

The variation of C_p across the band in the unloaded primary condition is essentially a straight line, from which the effective secondary coil inductance can be calculated. The variation of R_p across the band for the same unloaded condition approximates a constant Q law as might be expected, though a self-resonance of the unloaded primary coil causes a deviation of this curve as the value of $1/f^2 = 0.005$ is approached (represented by point C in Fig. 1).

The variation of C_p across the frequency band for the loaded primary condition shows a deviation from the unloaded value that increases as the frequency decreases. This represents an increasing amount of negative inductance transferred from the primary circuit to the secondary circuit, indicating that a primary circuit resonance is being approached (represented by point A in Fig. 1). This resonance is due to the primary inductanace resonating with the capacitive reactance of the antenna at some frequency below its quarter-wavelength resonance. At the same time, a second primary circuit resonance has been shifted downwards to a point just above the band (point B in Fig. 1), again resulting in detuning of the secondary. This resonance is due to the primary inductance resonating with the capacitive reactance of the

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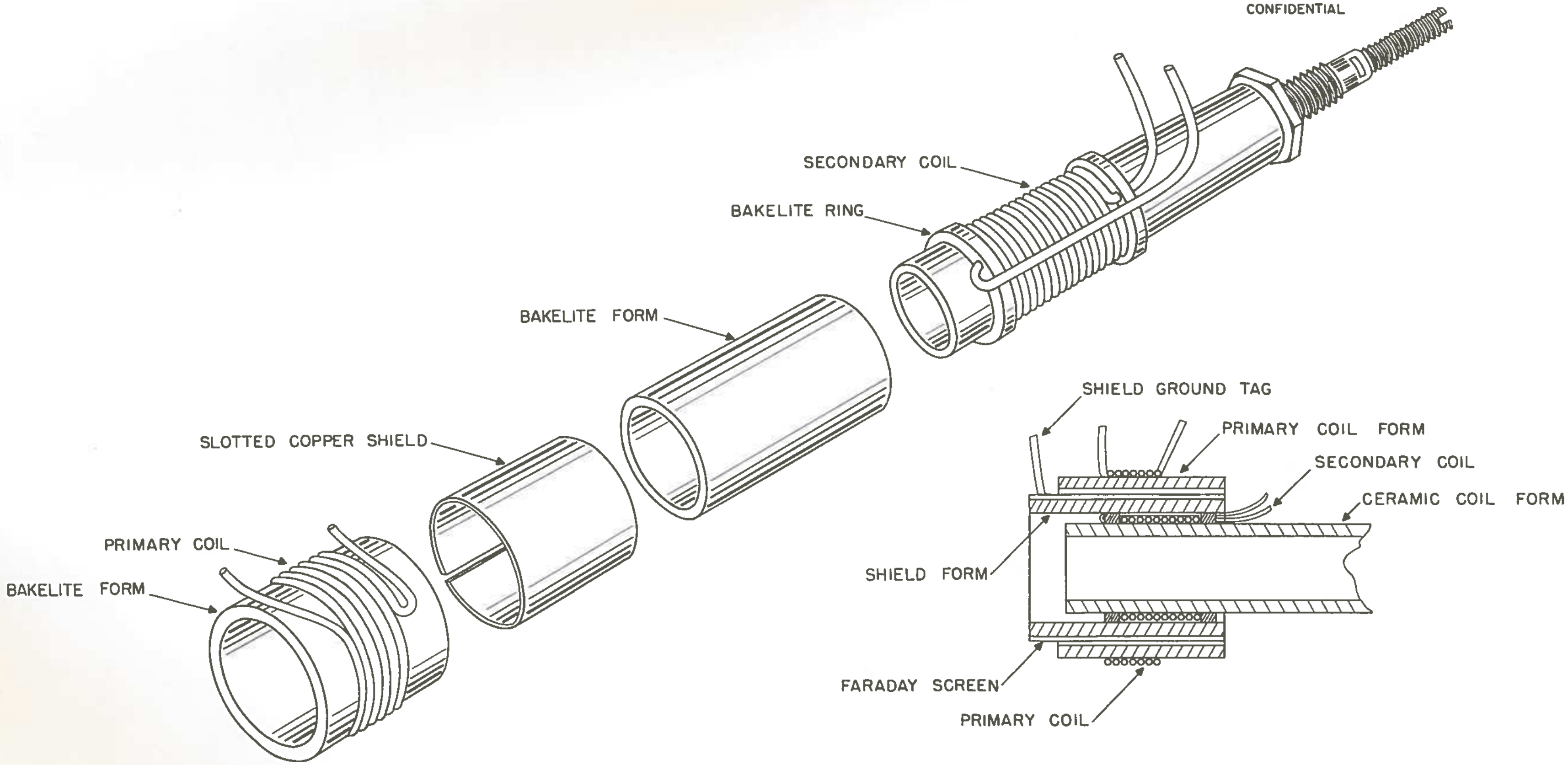

FIG. 2. ASSEMBLY OF INPUT COIL

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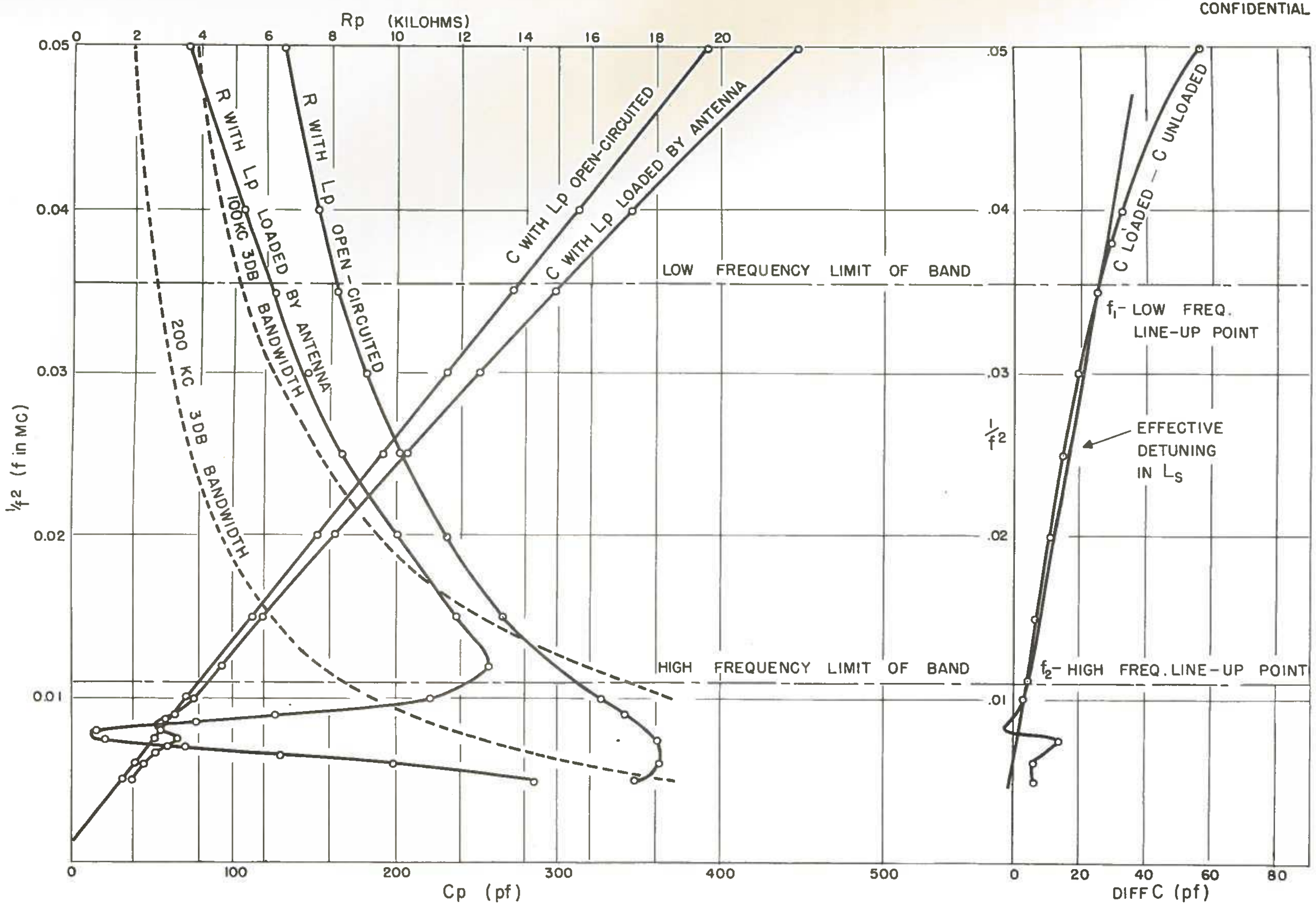

FIG. 3. MEASURED CHARACTERISTICS OF A COUPLING CIRCUIT

antenna at a frequency between its half-wavelength and three-quarter wavelength resonances, though somewhat lowered by the self-capacity of the coil and the stray capacity of the input circuit assembly.

The difference between the values of C_p with the primary coil loaded and C_p with the primary coil open-circuited represents the detuning of the secondary circuit produced by the load. In practice, however, the value of the secondary inductance can be readjusted so that the effective detuning is reduced to the amount this difference plot deviates from a straight line (in the case of tuning capacitors with a straight line frequency law) joining the two frequency line-up points near the top and bottom of the band, as represented by f_1 and f_2 in Fig. 3. It should be noted here that since the difference between C_p loaded and C_p open-circuited determines the detuning, it is advisable to make both these measurements in turn at each frequency setting. Thus the exact frequency for each measurement does not have to be known, the accuracy of the frequency scale on the measuring instrument being sufficient to produce the required results.

The measured values of R_p across the band for the loaded condition give a direct indication of the transfer efficiency of the circuit, a reduction by a factor of two from the open-circuited values of R_p representing the maximum efficiency condition. At the same time, the resulting bandwidth of the secondary circuit can be compared with the desired bandwidth curves (also shown in Fig. 3) which can be calculated and plotted as values of parallel resistance R_p against $1/f^2$.

The design procedure of the input circuit in the above example can thus be summarized as follows. The primary and secondary coils were initially constructed as determined by the tuning capacitance and the antenna impedance. The size of the primary inductance was then increased until the detuning caused by the second primary circuit resonance, represented by point B on Fig. 1, was just above the band, this condition being determined by measurement. The coupling was then increased until the detuning caused by the presence of the primary resonance below the band was just within the acceptable limits. Further, the resulting bandwidth closely approximated the required 3-db bandwidth of 100 kc/s. If the resulting bandwidth had been too narrow, resistive damping of the secondary circuit would have been required. If the bandwidth had been too wide, an effort to increase the initial Q of the coils would have been made. Failing this, the coupling would have been reduced to produce an acceptable compromise.

OVERALL PERFORMANCE

1) 4-element Adcock System

The dimensions of the 4-element Adcock antenna referred to in Fig. 1 are as follows:

Spacing of elements	-	5 meters
Size of elements	-	16-inch diameter cages, 20 feet long
Size of downleads	-	2 feet long, conical
Antenna feeders	-	200-ohm, radial

The antenna was coupled to receiver AN/GRD-501 through circuits derived by the design procedure presented above. The frequencies of the primary circuit resonances were satisfactorily controlled in Bands 1, 2, and 4, but some difficulty was encountered in the design for Band 3. The stray capacity of the input switching unit of the receiver lowered the effective capacitive reactance of the antenna in the vicinity of the high end of Band 3 to such an extent that it became impractical to use a primary inductance small enough to keep the resulting resonance above the band. The stray capacity of this unit was made up of the capacity of several relays which were required for the injection of a reference signal at the receiver input, and was minimized by the use of the best quality RF relays obtainable.

The final design included the use of a large primary inductance and an additional length of feeder switched in for this band to shift the primary resonance below the band. This compromise was accepted on the basis of a sensitivity comparison between several designs in which the resonances were located at various positions in the band. The use of a larger primary inductance without any feeder extension proved unsatisfactory because of the limit imposed by the self-resonance of the primary coil. It became apparent, however, that some advantage could be gained if the high frequency limit of the band could be reduced from 17 mc/s to about 15 mc/s, thus allowing the use of a small primary inductance to keep the resonance above the band.

The effects of antenna parallel resonances should not be neglected. Though the high values of antenna impedance at these frequencies do not cause detuning of the secondary circuits, their exact values control the relative phases and amplitudes of the primary currents. It is very important, therefore, that these resonances occur at exactly the same frequencies in each antenna element to avoid instrumental error in the system. For this reason, shunt capacity trimmers were used at each input terminal of the input switching unit to lower the frequencies of these resonances for equalization. Resistive balancing controls were found to be unnecessary because the Q of the antenna elements proved to be extremely stable. The effects of these unbalances are found at approximately 12 mc/s and 25 mc/s, though the inherent low Q of the "fat" elements makes the adjustments fairly non-critical.

2) <u>8-element Adcock System</u>

A second twin-channel receiver of the same electrical design was coupled to an

8-element Adcock antenna using the same design procedure and performance specifications as in the first system. The measured impedance curves of this antenna are shown in Fig. 4 and the dimensions are tabulated below.

Spacing of elements	-	9 meters
Size of elements	-	$2\frac{1}{2}$-inch diameter, $22\frac{1}{2}$ feet long
Size of downleads	-	1-inch diameter, 2 feet long
Antenna feeders	-	200-ohm to Tee junction, 100-ohm radial
Half-angle	-	$27\frac{1}{2}°$ (between elements of a pair)

It will be noticed that there is a discontinuity in the impedance curves between Bands 3 and 4. This resulted when series damping resistors were inserted at the Tee junction for Band 4 operation to reduce the effects of mutual impedance between elements (as shown by the irregularity of the impedance characteristics between 19 and 24 mc/s).

Primary circuit resonances were kept out of Bands 1 and 2, but resistive damping was employed to reduce the detuning effects of these resonances in Bands 3 and 4. As with the 4-element antenna, the frequencies of parallel resonances were lowered by the shunt capacity in the input switching unit, the exact balance between the individual pairs of elements again being controlled by capacitive trimmers. Adjustment of these trimmers was most critical at the second parallel resonance where the antenna Q was high and a slight unbalance caused large bearing errors (about 7° at 16.3 mc/s) over a very narrow bandwidth. The effect at the first parallel resonance, on the other hand, was reduced to an acceptable amount by the insertion of small series damping resistors at the Tee junctions. This same effect was quite unnoticeable at the third parallel resonance in Band 4 where the Q of the damped antenna was relatively low.

3) Sensitivity Comparison

Upon completion of these coupling circuits, a sensitivity comparison was made between the two antenna systems. A field test oscillator was located at a point equidistant from the two antennas (about 400 feet) and the signals on the first RF grids of the two receivers were compared using a signal generator substitution method. Assuming equal field intensities at the centers of the two antenna systems, the ratio of the signals on the first grids of the two receivers provided a measure of the relative sensitivities of the two systems, including the input coupling circuits.

The results of the comparison are shown in Fig. 5. The calculated advantage of

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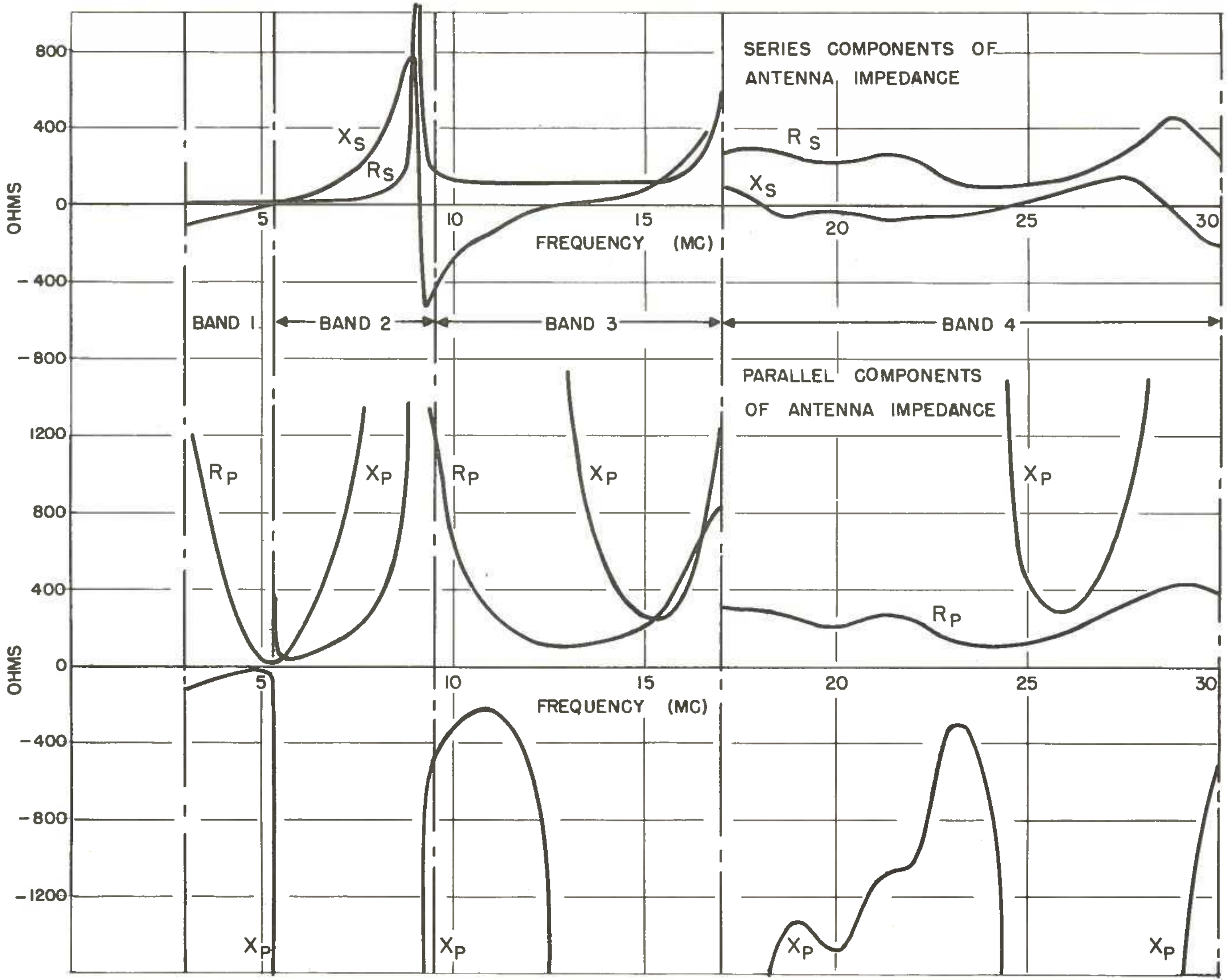

FIG. 4. MEASURED IMPEDANCE CURVES OF AN 8-ELEMENT ADCOCK ANTENNA

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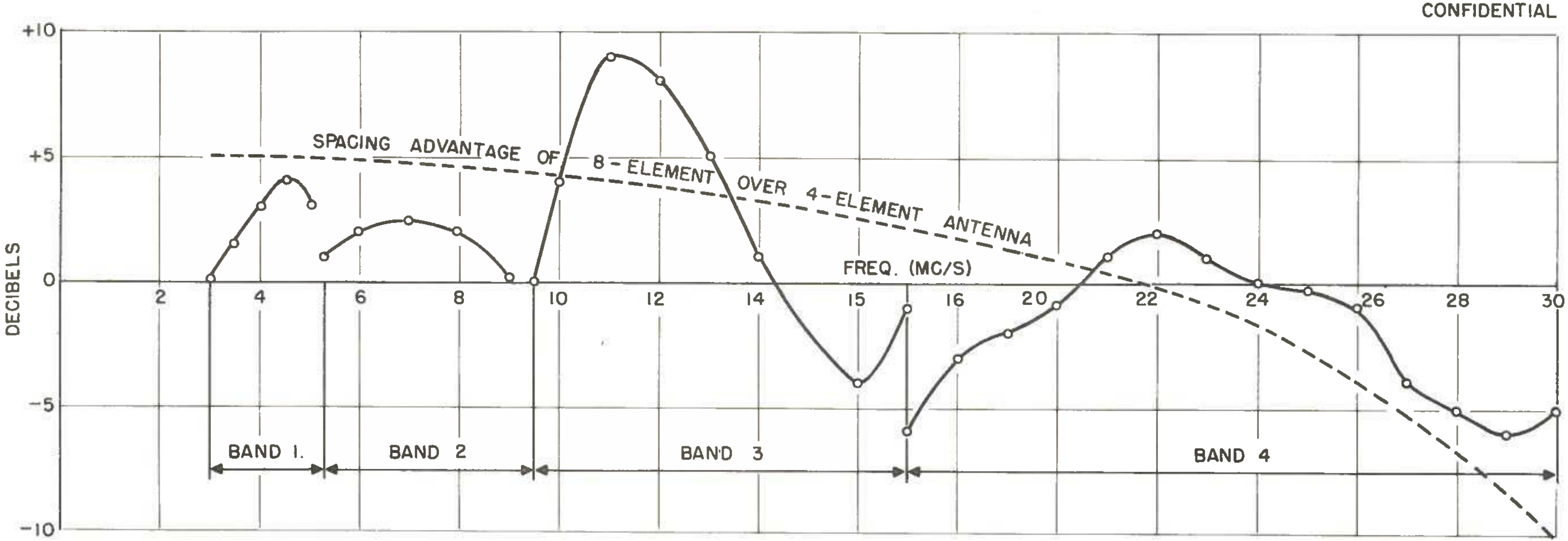

FIG. 5. RELATIVE GAIN OF 8-ELEMENT OVER 4-ELEMENT ADCOCK ANTENNA

the 8-element antenna over the 4-element antenna due to their spacings is also shown. There is a considerable difference between the two curves which can be accounted for as follows.

a) Band 1 - The spacing advantage of the 8-element antenna has been reduced considerably at the low end of the band. In both designs a primary circuit resonance is located about 40% below the band, at which point the primary and secondary circuits are overcoupled, but it appears that the low Q elements of the 4-element antenna provide an optimum load over a wider range of frequencies away from the resonance. Experimental tests have indicated that about 8 to 10 db can be gained by tuning the antenna and adjusting for optimum coupling.

b) Band 2 - The situation is similar to that in Band 1, in that there are primary resonances above and below the band in both designs, but the lower Q elements of the 4-element antenna again provide efficient coupling over a greater bandwidth away from the resonance.

c) Band 3 - In the 8-element system, a primary circuit resonance occurs at about 12 mc/s, while in the 4-element system there is a resonance below the band and another near the top of the band (about 16 mc/s). Since the maximum coupling coefficient is limited by the permissible detuning, a high degree of overcoupling between the primary and secondary circuits is avoided. Thus the high coupling efficiencies that exist in the region of the primary resonances favour the respective systems as shown.

d) Band 4 - The location of the primary circuit resonances again determines the relative efficiencies over the band, the resonance in the middle of the band (23 mc/s) in the 8-element system providing greater efficiency in that region, and the resonances above and below the band in the 4-element system providing greater efficiency in the end regions of the band.

CONCLUSIONS

From the foregoing discussions it may be concluded that the input coupling circuit design problems presented by primary circuit resonances can generally be solved by manipulation of coil sizes and antenna feeder lengths to control the frequencies of these resonances. A compromise between sensitivity, bandwidth and detuning must be accepted in most cases, and this is usually a satisfactory solution. The use of antenna dummy circuits can simplify the measurement test setup, but considerable care must be taken to ensure that the dummy circuit impedance very closely resembles the antenna impedance, especially in the vicinity of the antenna series resonances, where the total impedance is low. In any case, such dummy circuits are desirable for use during alignment of the secondary RF circuits, as the correct loading must be applied to the primary to ensure proper tracking between the channels; otherwise, an external source of radiated signal must be used with the antenna itself supplying the specified load.

The results of the sensitivity comparison measurements show the effects of these coupling circuits on overall sensitivity. The inherent sensitivity advantage of the 8-element antenna has been considerably reduced by the more favourable impedance characteristics of the 4-element antenna which allow a relatively greater degree of coupling efficiency to the receiver.

Finally, it becomes apparent that one can sometimes be placed at a considerable disadvantage initially by an unfortunate choice of frequency bands. If the frequency ranges can be chosen to locate the antenna resonances favourably, the overall performance can be optimized.