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RF BONDING IMPEDANCE STUDY

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FOREWORD

This report describes one phase of a program conducted for Rome Air Development Center under Contract AF30(602)-3282, Project No. 4540, Task No. 454003. Technical monitoring was under the cognizance of Mr. Wayne E. Woodward of the Vulnerability Reduction Branch. (EMCVI-2)

The work described was performed at the Georgia Institute of Technology Engineering Experiment Station under the general supervision of D. W. Robertson, Head, Communications Branch. The Project Director was W. B. Warren, Jr. The authors of this report are H. W. Denny and W. B. Warren, Jr. The contributions of J. A. Hart, Jr., and K. G. Byers, Jr., to this effort are acknowledged.

This report has been reviewed and is approved.

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ABSTRACT

The significant factors affecting bonding impedance at high frequencies are examined and the reactance of the bonding structure is shown to be the major contributor. Resonant effects caused by stray capacitances are examined and an equivalent circuit is presented to explain the experimentally observed variation with frequency of the bonding impedance.

Several techniques for the reduction of bonding impedance are described and experimentally evaluated.

A technique for continuous visual display of bonding impedance versus frequency is presented and its suitability for field use is noted.

TABLE OF CONTENTS

Contents | Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

1. Introduction

The electromagnetic isolation of electronic equipments is basic to the reduction of interference. Isolation is normally obtained through techniques involving shielding, grounding, and filtering. In each of these techniques the "bond" or electrical reference between components, assemblies, equipments, or an entire complex is of paramount importance. To be effective, the bond should exhibit a negligible impedance so as to establish each electromagnetically exposed element at a neutral or "ground" reference potential. The usual criterion for judging bond effectiveness is based on the measured impedance of the bond over a particular frequency range. For example, MIL-B-5087A specifies that the bond impedance must be no greater than 80 milliohms for any frequency below 20 MHz.

Except for fairly recent studies, most of the emphasis on bonding and grounding has been concentrated at dc and low frequencies. A literature survey conducted by Georgia Tech[1] has revealed some 477 sources of information which were more or less directly concerned with bonding at low frequencies. More recent studies have dealt with the rf characteristics[2] of bonds as well as instruments[3,4] for evaluating the quality of a bond. Grounding concepts as they apply to propagation, power systems, and lightning protection have also been fairly well defined.[5,6]

The work reported here has been concerned with the identification of those factors which permit the rapid assessment of bonding impedances in laboratory as well as in field installations. Although some consideration was given to the low frequency behavior of bonding impedances, by far the larger amount of effort was expended in the investigation of bonding impedances at frequencies in the 1 MHz to 200 MHz range. Methods of bonding impedance reduction were examined and several techniques for lowering this impedance over certain frequency ranges were studied.

2. Discussion

2.1 System of Measurement of Bonding Impedance

Two methods are generally used to measure the impedance of a bond at RF frequencies. In the first method, the unknown bonding impedance is made an integral part of a resonant device, such as a cavity or resonant circuit, and the effect of the impedance on the Q of the resonant device is observed. By noting the reduction in Q when the bond is connected to the resonant device, the unknown impedance can be approximated. In the second method, the unknown impedance is used as the shunt element of a "T" attenuator. If the attenuator is connected between a source and load of known impedance, the resulting insertion loss of the attenuator can be simply related to the magnitude of the unknown bond impedance.

The insertion loss technique was selected as the more appropriate method for measuring the impedance of practical bonding straps. This selection was motivated primarily by two factors. First the Q degradation method requires the adjustment of the bonding structure to a resonant condition at each frequency at which the impedance is to be measured, and second, the physical arrangement of many bonding structures makes them very difficult to incorporate into the necessary resonant arrangement without introducing appreciable error in the measurement by means of the connecting impedances.

The insertion loss method has neither of these disadvantages. It provides a straightforward means which is inherently insensitive to small variations in the connection impedances in connecting the unknown impedance to the measurement system. In addition it does not require continuous adjustment when making measurements over a wide range of frequencies.

The insertion loss technique used in obtaining the bonding impedance data contained in this report is a modification of the technique reported in U. S. Naval Air Development Center report number ADC EL-172-50. With this modified arrangement useful data was obtained on impedances whose magnitudes ranged from 10^{-6} to 10^{3} ohms and at frequencies ranging from 10 KHz to 400 MHz.

Figure 1 is an equivalent circuit of an impedance measurement device, operating on the insertion loss principle, which was designed to operate in a coaxial system. Two isolation resistors, R_1 and R_2, are placed in series with the connections to an unknown impedance forming a "T" network. As long as the connection impedances r_{C1}, r_{C2}, r_{C3}, r_{C4}, ωL_1, and ωL_2 are small with respect to the isolation resistance, their effect on the circuit is negligible. In actual practice, the isolation resistors are chosen to be large with respect to the unknown impedance as well as the connection impedances over a frequency range as wide as possible.

Assuming that the isolation resistor, R_1, is large with respect to $r_{C1} + r_{C2} + j\omega L_1 + Z$, the input current, I_i, is given by

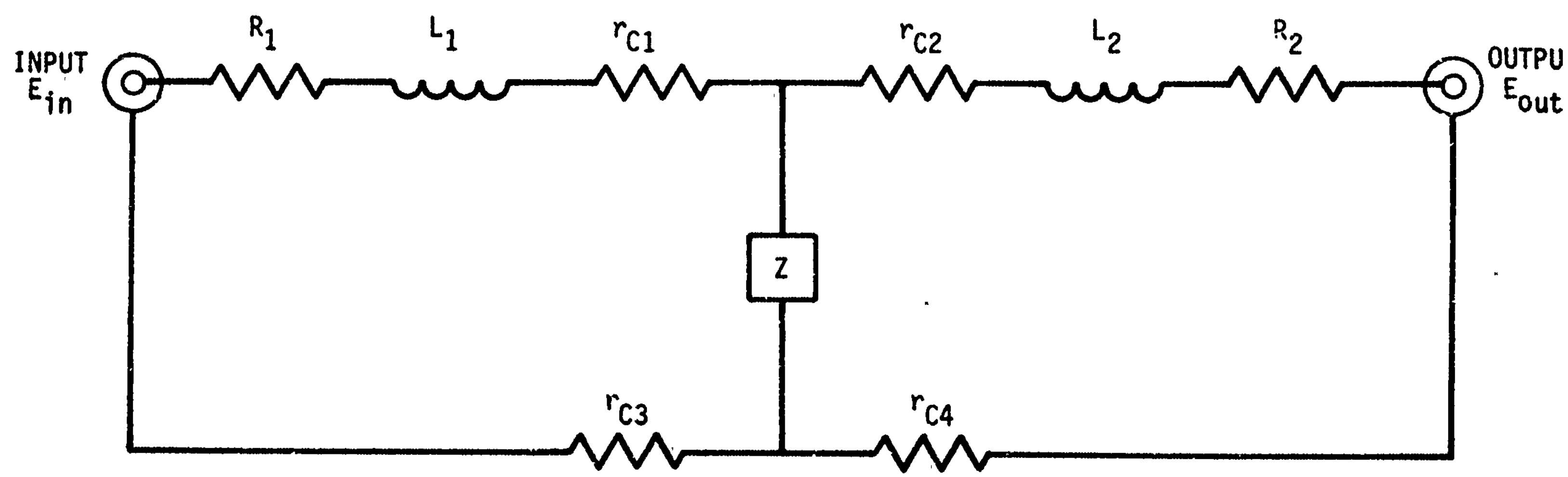


Figure 1. Equivalent Circuit of the Insertion Loss Measuring Setup.

$$I_i = \frac{E_{in}}{R_1} \quad . \tag{1}$$

If the bond impedance is small with respect to R_2, all of the input current will flow through Z and develop a voltage drop across Z. This drop is

$$V_Z = \frac{E_{in} Z}{R_1} \quad . \tag{2}$$

The circuit to the left of ʼnd including Z may be replaced by its Thevenin equivalent with an open circuit voltage of V_Z and an impedance of Z. If, as before, the isolation resistor, R_2, is large with respect to $r_{C3} + r_{C4} + j\omega L_2 + Z$ the output current, I_o, is

$$I_o = \frac{V_Z}{R_2 + 50} \quad , \tag{3}$$

assuming operation into a 50 ohm load impedance.

The output, E_{out}, is then

$$E_{out} = \frac{50\ V_Z}{R_2 + 50} \quad . \tag{4}$$

Substituting the expression for V_Z from (2) gives

$$E_{out} = \frac{(50)(E_{in}\ Z)}{R_1(R_2 + 50)} \quad , \tag{5}$$

or

$$|Z| = \frac{R_1(R_2 + 50)}{50} \left| \frac{E_{out}}{E_{in}} \right| \quad , \qquad (6)$$

which directly relates the bonding impedance magnitude to the insertion loss through the network.

In order to simplify the process of calculating the bonding impedance corresponding to a measured value of insertion loss, Equation (6) has been expressed in the form of the nomogram of Figure 2. Lines on the nomogram are shown for three different values of isolation resistors. The impedance corresponding to a particular value of insertion loss is determined by finding the loss value on the abcissa and relating it to the bond impedance value at the intersection of the loss value and the line for the particular value of isolation resistor being used.

For example, an insertion loss of 40 db corresponds to a 1 ohm bond impedance if the test fixture has 50 ohm isolation resistors.

2.2 Contact Impedance of Bonds

The insertion loss measurement technique was used to study the contact impedance of bonds constructed with different materials. Figure 3 shows the construction of the test fixture used to compare the contact region impedance of bonds formed with several different materials. The bond itself consists of the mating surfaces between a cylindrical foot projecting from the top bond block and the surface of the lower bond block. The two

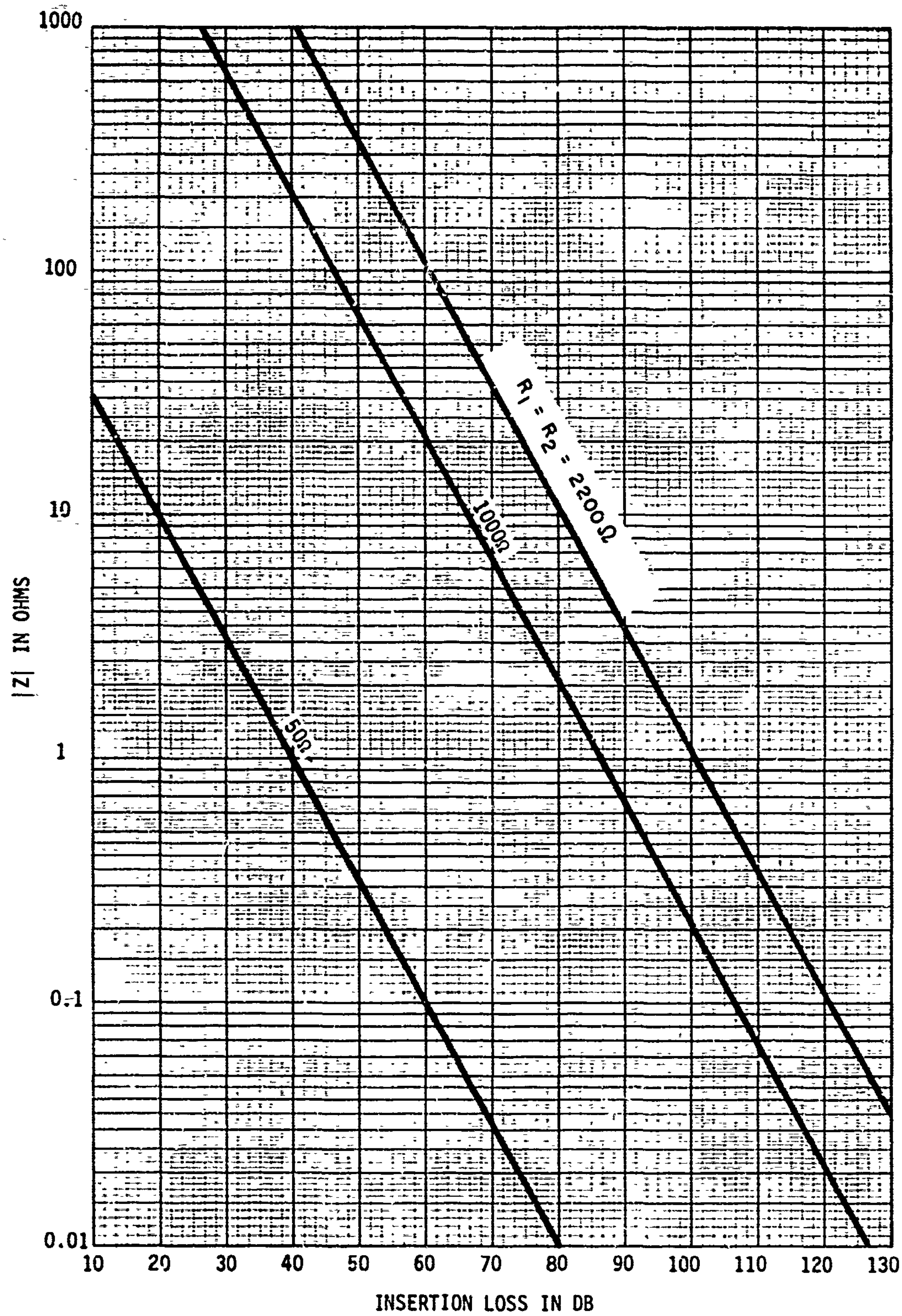


Figure 2. Nomograph Relating the Magnitude of the Impedance to the Insertion Loss.

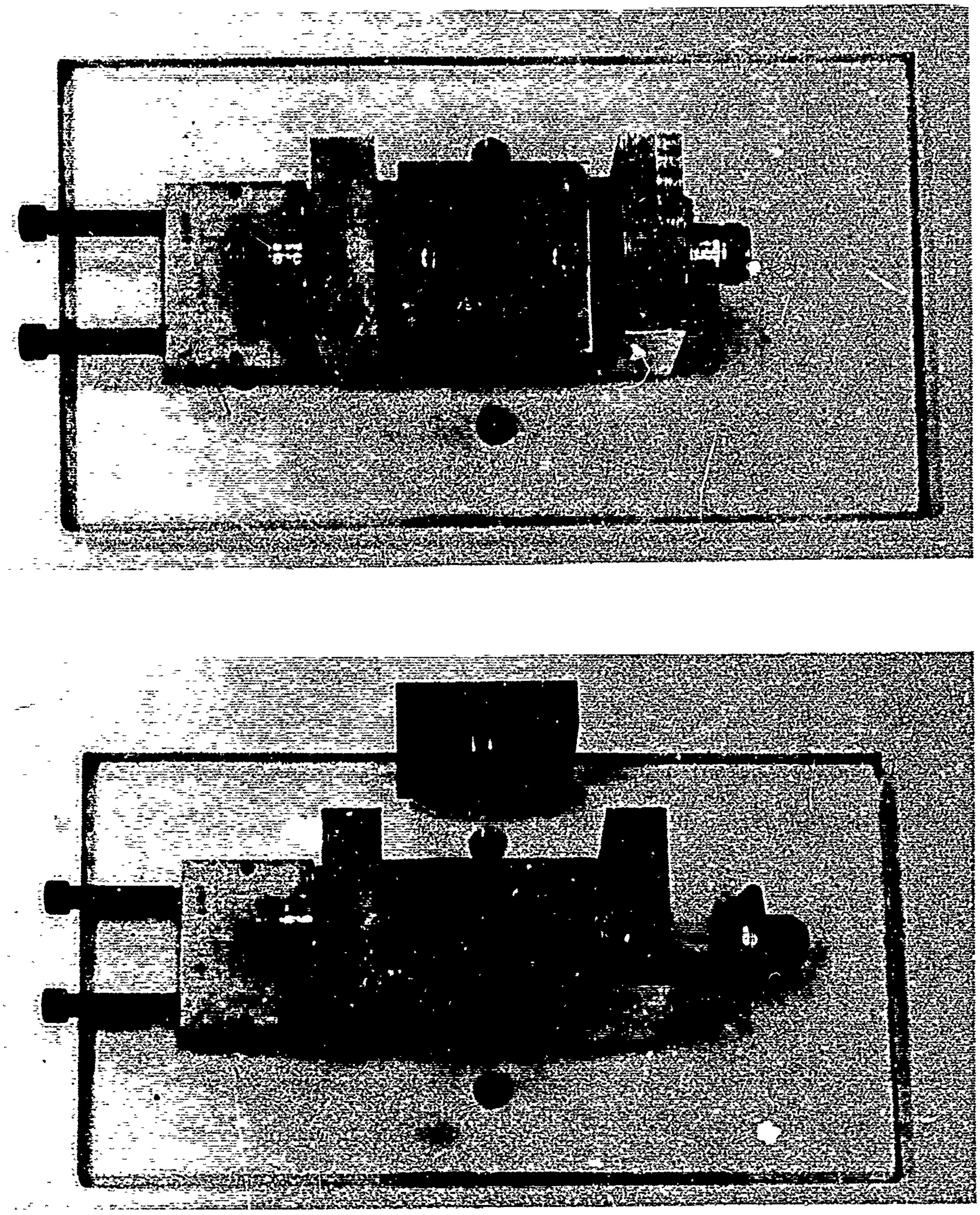


Figure 3. Insertion Loss Measuring Test Fixture.

bond blocks are held together by a vertical bolt which runs through both blocks but is insulated from them. By tightening the bolt, the pressure on the contact region can be varied. The two end blocks carry the input and output coaxial connectors as well as the 50 ohm isolation resistors which are connected in series with the center pins of the two coaxial connectors. The other leads from the isolation resistors are attached by screws to the top bond block. The right hand end of Figure 3 is permanently fastened to the polystyrene base plate and the assembly is held together by the pressure exerted by the two horizontal bolts pushing against the left hand end block.

Using the test fixture of Figure 3, the variation of impedance with frequency was measured for bonds formed with upper and lower bond blocks of steel, aluminum, and brass. A reference bond, in which the upper and lower bond blocks were machined from one solid piece of aluminum, was also tested to permit the identification of that portion of the measured bond impedance which was due to the contact resistance and that portion which was associated with the inherent resistance of the material from which the bond blocks were formed.

The curves of Figure 4 show the measured variation of bond impedance with frequency of several test bonds as well as that of the aluminum reference block. The impedance of the reference block increases in proportion to frequency indicating that it acts essentially as a pure reactance at all the frequencies at which tests were performed. Consequently, the low frequency flat portion

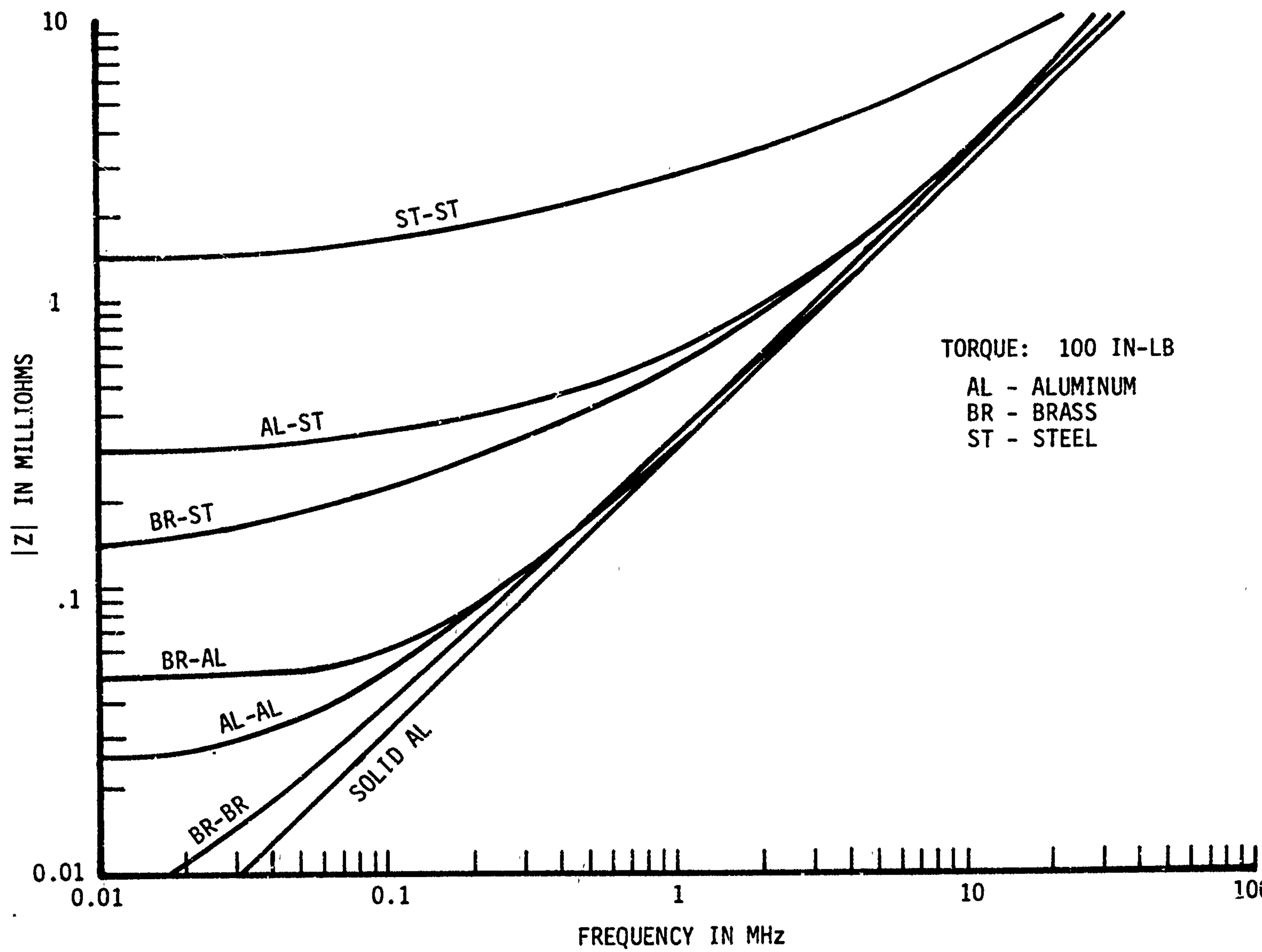


Figure 4. Frequency Variation of the Bonding Impedance Between Several Materials.

of the impedance curves of the test bonds can be attributed to the resistance of the contact region. Generally those bonds involving at least one steel surface show higher impedances than those of brass or aluminum. This higher impedance is caused both by a higher contact resistance and by the higher inductance of the bond structure which results from the permeability of the steel being considerably larger than that of either the aluminum or brass. These results are essentially in conformance with those determined by other investigators for similar bond configurations[7].

Although there is a considerable range of impedance variation at low frequencies between the several different materials tested, the impedance versus frequency characteristics of Figure 4 all approach that of a pure reactance at high frequencies. Since the test bonds were constructed in such a manner as to minimize the inductance of the bond structure, it seems likely that most practical bonds which involve even a small length of bonding strap will have an inductance that exceeds that of the test bond. Consequently, it can be concluded from the curves of Figure 4 that at frequencies above approximately 1 MHz, the overall impedance of most practical bonding straps is set by the reactance of the bonding structure and that the effects of small variations in the resistance of the bond contact region are relatively unimportant as long as nonlinear effects are not present.

Tests were also run to determine the sensitivity of the bond contact resistance to variations in contact pressure at frequencies where the contact resistance is a significant part of the bond impedance. The manner in which contact pressure affected the contact resistance of test bonds formed of three different materials is shown in Figure 5. The tests were made at 50 KHz. This frequency is high enough to show any effects associated with the ac as opposed to the dc contact resistance, and it is still low enough to insure that the contact resistance of the bond being measured is considerably larger than the inductive reactance of the bond structure. The torque values along the abcissa represent the torque applied with a torque wrench to the vertical connecting bolt which held the bond assembly together. The curves indicate that torques above about 40 in-lb produce relatively small reductions in contact resistance. The contact resistance at low contact pressures was found to be widely variable, with variations by a factor of two or three being recorded on repeated tests. This result is not unexpected since the area of contact at low pressure is dependent on the random alignment of small imperfections in the two bond surfaces, and it is unlikely that an identical alignment could be obtained when the bond structure was dismantled and then reassembled for successive tests. More consistent behavior was observed at higher bonding pressures where the slope of the resistance versus pressure curve becomes relatively flat. Such behavior indicates that as

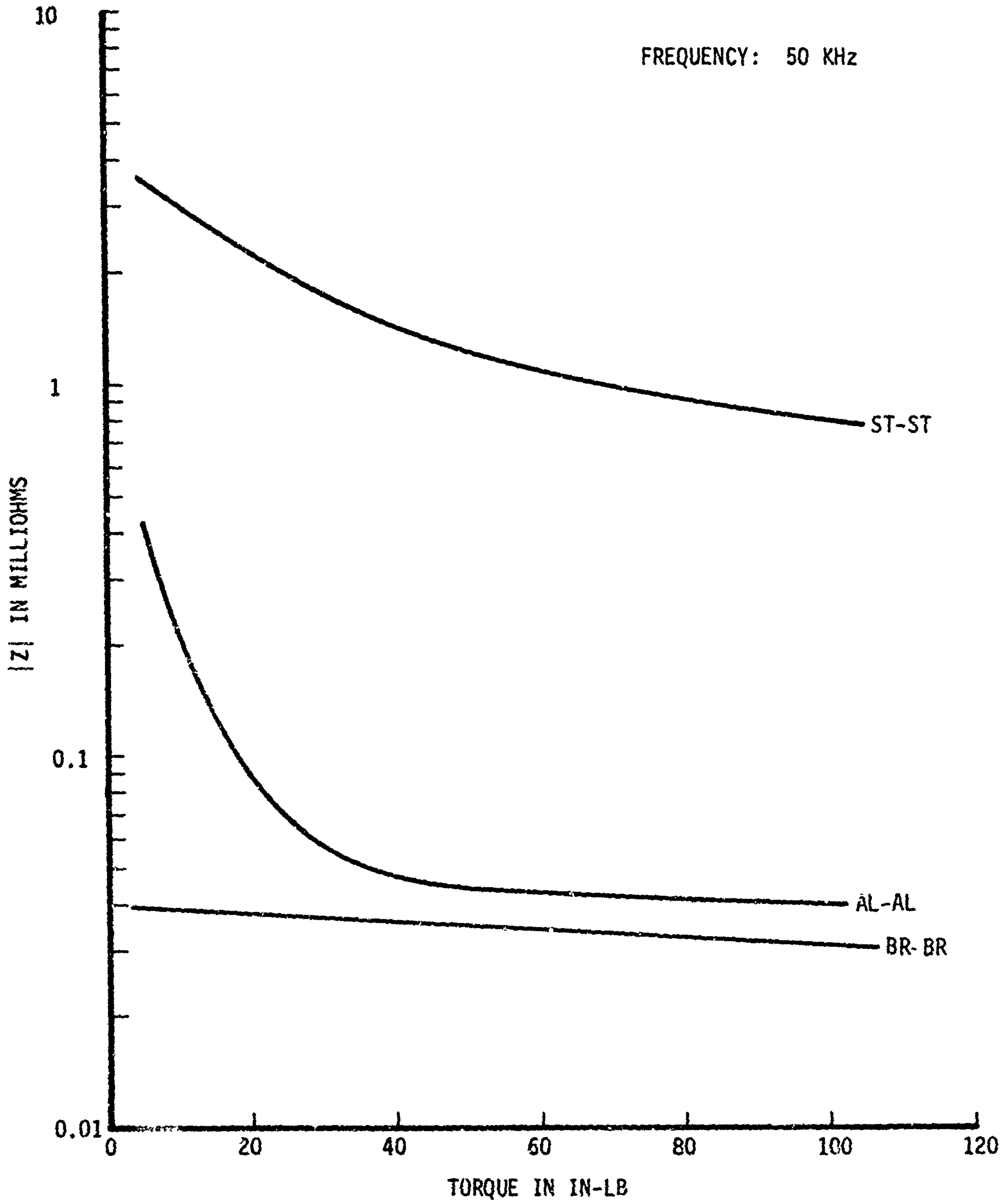


Figure 5. Bonding Impedance Variation As a Function of Pressure.

long as care is taken to apply a relatively firm pressure in forming a bond, contact pressure should not be a significant factor in controlling the overall bond impedance.

2.3 Bonding Impedance Equivalent Circuits

In order to calculate the behavior of the bonding impedance of straps as used in a practical bonding situation it is necessary to use an equivalent circuit which adequately describes the physical situation in which the bonding strap is being used.

An equivalent circuit of a bonding strap has been used by other investigators[8,9] to compute the reactance of bond straps at high frequencies, but these studies generally have not included the resonance effects produced by the combination of the strap reactance and the reactance of the equipment being grounded. A series of measurements were made with practical bonding straps to obtain data on which to base an equivalent circuit. Since the original impedance measuring test fixture of Figure 3 was difficult to attach to a conventional bond strap or to an equipment cabinet, a new test fixture was constructed. The new fixture was fabricated as a three terminal box with two BNC terminals to provide connections for the signal source and the detector. The third terminal, which provides for the connection of the unknown impedance, was mounted on a corner of the box to minimize the capacity between the device and the chassis or cabinet being measured. When in use, the case of the test fixture is connected to the ground plane through the use of threaded holes on the bottom of the test fixture. The positions of the isolation and matching resistors as well as the overall construction of the device are shown in the photograph of Figure 6. A metallic shield which minimizes stray coupling between the input and output terminals is also visible in the photograph.

In general, the accuracy of impedance measurement at high frequencies is limited by the degree of coupling between L_1 and L_2 of Figure 1. Other contributing factors are the shunt capacitance between the isolation resistors R_1 and R_2, and the lead inductance inherent to the common path from the junction of r_{C1} and r_{C2} to Z and from Z to the junction of r_{C3} and r_{C4}. The effects of coupling between L_1 and L_2 and the shunt capacitance between R_1 and R_2 were minimized by shielding, and the common lead inductance was reduced by making the junction of the series arms of the "T" attenuator as physically close to Z as possible. Nevertheless, in some of the measurements this inductance set an upper frequency limit on the measurement of the magnitude of Z.

Using the test fixture of Figure 6, preliminary measurements were made on four different conductor types to determine the impedance magnitudes to be expected at high frequencies for simple straight bonding straps. The conductors examined were a copper strap, a tinned steel strap, a rigid brass tubular strap, and a braided copper strap. These particular straps were selected as representative of the types that might be encountered in practical bonding situations. Figure 7 illustrates the results of the

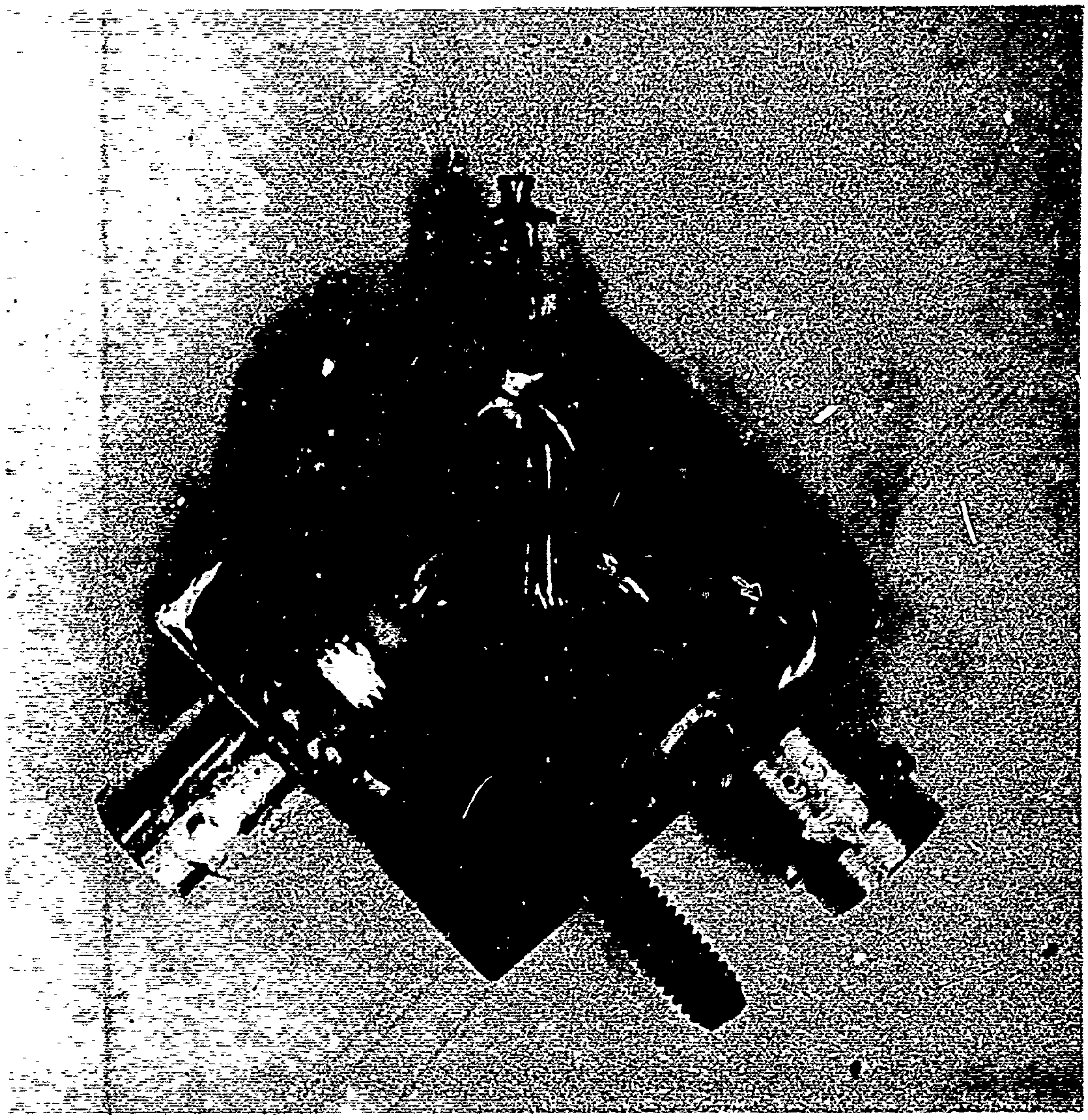


Figure 6. Modified Test Fixture.

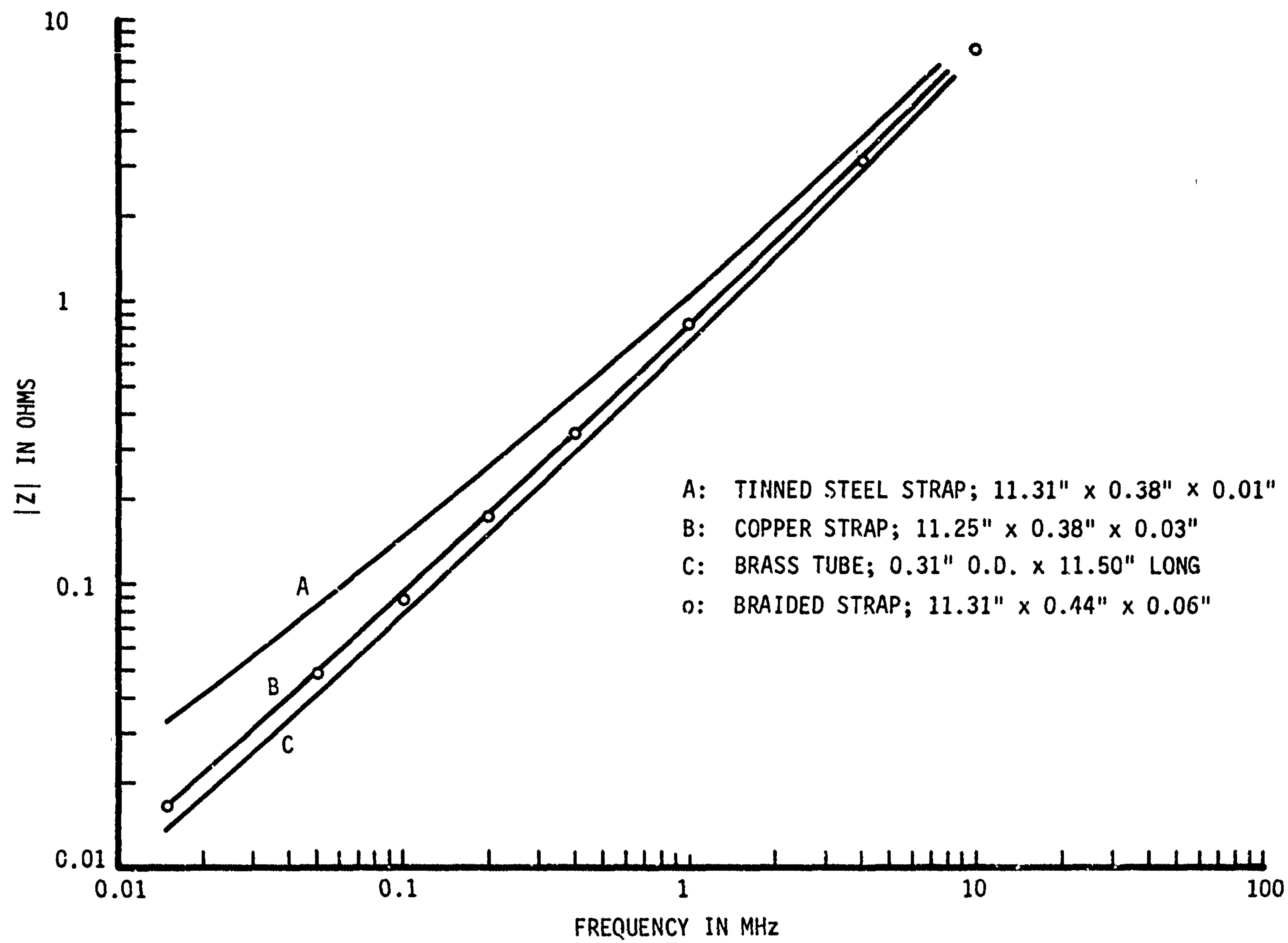


Figure 7. Frequency Variation of the Impedance of Simple Conductors.

measurements of the impedance of these four bonding straps. All the straps show an impedance which is directly proportional to frequency, indicating that the straps act essentially as pure inductances over the frequency range tested. The higher inductance indicated for the tinned steel strap results from the fact that steel has a higher permeability than brass or copper.

When the test bond straps were used to connect a piece of equipment to a ground plane, considerably different behavior of the impedance between the bond strap and the ground plane was observed.

An example of the measured variation of bond impedance with frequency at the bonding point of a typical ground strap and a R-361 receiver cabinet is shown in Figure 8. The cabinet is separated from the ground plane with a paper dielectric of approximately 0.004 inches in thickness. The length of the ground strap is 2-3/4 inches. Below about 10 MHz, the impedance behavior is governed by the strap inductance as evidenced by the proportionality between impedance and frequency. Above 10 MHz the impedance increases rapidly until a parallel resonance between the strap inductance and the case to ground capacitance occurs around 21 MHz. The parallel resonance is followed by a series resonance near 53 MHz. Measurements to 200 MHz showed a continued increase in impedance. The maximum impedance measured at parallel resonance was about 20 ohms which is about the maximum possible using 50 ohm isolation resistors in the measurement system. Since higher values were subsequently encountered, the isolation resistors were increased to a value of 2200 ohms to

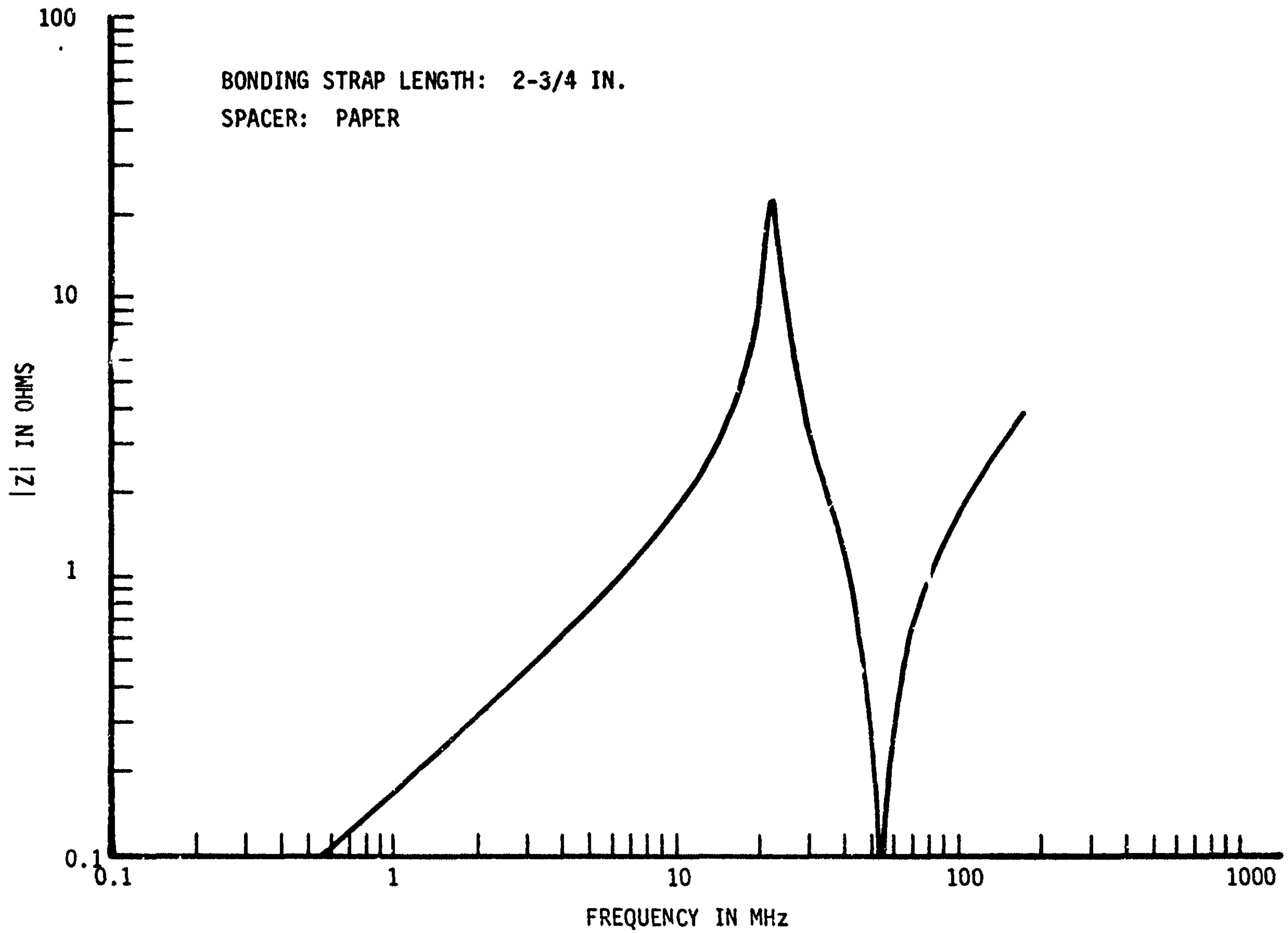


Figure 8. Bonding Impedance Versus Frequency for a Typical Receiver Cabinet and Ground Strap Combination.

permit the measurement of higher impedances.

If the bonding circuit consisted of simply the strap inductances in parallel with the case shunt capacitance to ground, then at frequencies above the resonant frequency of the combination, the bonding impedance should decrease with increasing frequency. In most of the measurements made with the insertion loss system, the expected parallel resonance was followed by a series resonance and subsequent increase in bonding impedance. Transmission line effects are not responsible for this behavior since the dimensions of the cabinet are only small fractions of a wave length at the frequency at which the series resonance occurs. The curves of Figure 9 show that the series resonant frequency shifts when the length of bond strap is changed. The impedance versus frequency characteristics shown in Figure 8 and Figure 9 can be explained by associating a series inductance, L_m, with the measurement system. The equivalent circuit that results from placing this inductance in series with the parallel circuit containing the strap inductance and case capacitance is shown in Figure 10. A brief analysis of the circuit of Figure 10 shows the location of the parallel and series resonant frequencies as well as the variation of the series resonance frequency.

The input impedance, Z, of the circuit of Figure 10 is

$$Z(j\omega) = j\omega L_m + \frac{\frac{j\omega L}{j\omega C}}{j\omega L + \frac{1}{j\omega C}} , \qquad (7)$$

which can be simplified to

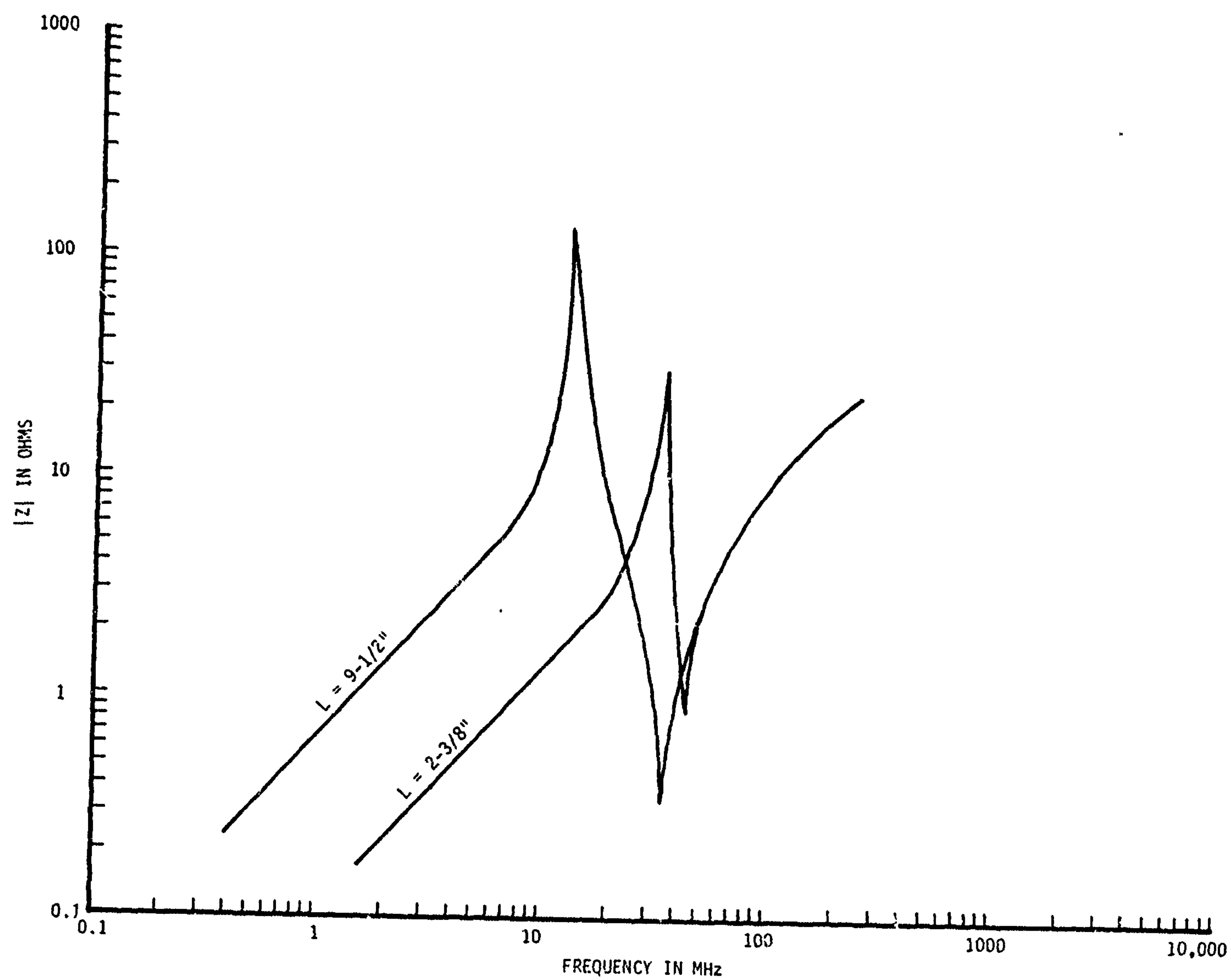


Figure 9. Bonding Impedance Variations for Two Lengths of Bond:.g Strap.

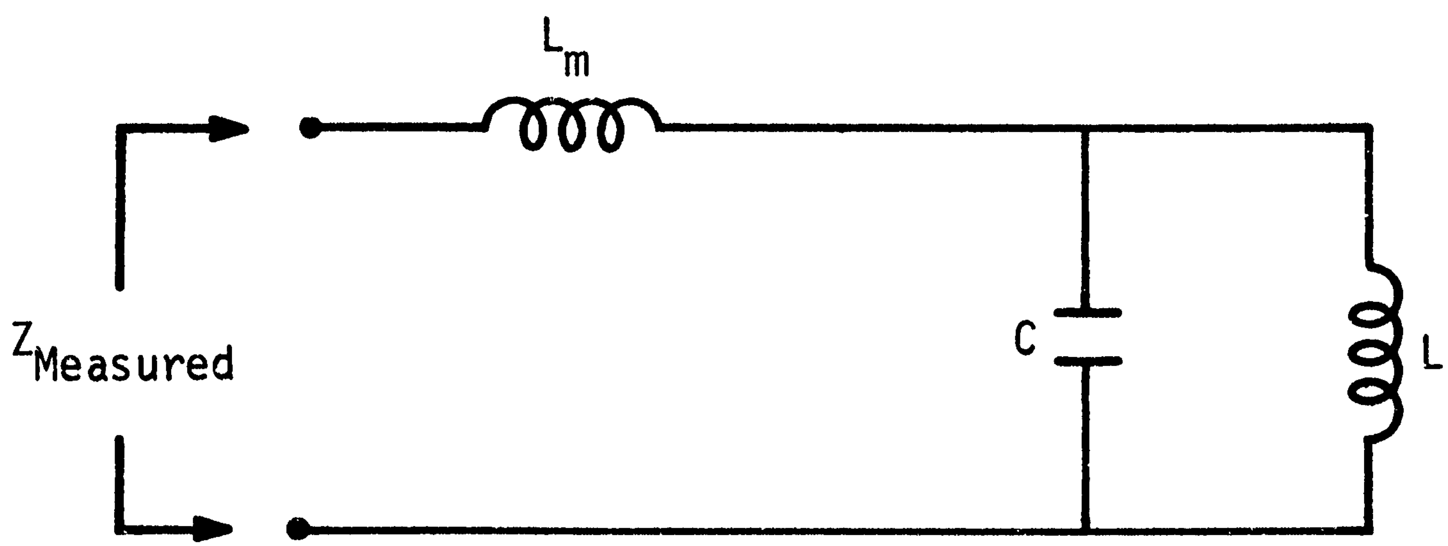


Figure 10. Equivalent Circuit of the Measurement Setup.

$$Z(j\omega) = j\omega L_m + \frac{j\omega L}{1 - \omega^2 LC} \quad . \tag{8}$$

The parallel resonant frequency, ω_p, is that frequency which makes the denominator of the second term of (8) equal to zero. Therefore,

$$\omega_p = \frac{1}{\sqrt{LC}} \quad . \tag{9}$$

Above the parallel resonant frequency the parallel combination of L and C acts like an equivalent capacitive reactance. Writing $Z(j\omega)$ in a form which shows this equivalent capacitance results in

$$Z(j\omega) = j\omega L_m + \frac{1}{j\omega C_{eq}} \quad . \tag{10}$$

The series resonant frequency, ω_s, is that frequency which makes (10) equal to zero. Therefore,

$$\omega_s = \frac{1}{\sqrt{L_m C_{eq}}} \quad . \tag{11}$$

Now factoring out $\frac{1}{j\omega}$ from the second term of (8) gives

$$Z(j\omega) = j\omega L_m + \frac{1}{j\omega}\left[\frac{-\omega^2 L}{1 - \omega^2 LC}\right] \quad . \tag{12}$$

From (10) and (12) the equivalent capacitance is

$$C_{eq} = \frac{1 - \omega^2 LC}{-\omega^2 L} \quad . \tag{13}$$

Substituting (13) in (11) and letting $\omega = \omega_s$ gives

$$\omega_s^2 = \frac{1}{L_m C - \frac{L_m}{\omega_s^2 L}} \quad . \tag{14}$$

Solving (14) for ω_s yields

$$\omega_s = \frac{1}{\sqrt{\left(\frac{L_m}{1 + \frac{L_m}{L}} C\right)}} = \frac{1}{\sqrt{L_{eq} C}} \quad . \tag{15}$$

From Equation (15), it can be seen that as L increases, the equivalent series inductance, L_{eq}, increases which lowers the series resonant frequency for a fixed value of L_m. The value of L_m for the text fixture of Figure 6 was evaluated by short circuiting the test terminals of the fixture with a very short, wide copper bar. A set of insertion loss measurements were then taken over a range of frequencies. These results indicate that the values of L_m for the fixture with 50 ohm isolation resistors is approximately 0.0032 μhy.

Although the equivalent circuit of Figure 10 adequately represents the behavior of the bonding impedance at the point of connection between the strap and the equipment case, a question arises as to whether or not the distributed inductance of the equipment case is sufficiently high to cause the impedance to the ground plane at points on the case removed from the strap connection point to differ widely from that described by the equivalent circuit. Measurements were made on the receiver cabinet at points other than at the junction of the ground strap and the cabinet in an effort to resolve this question. Only a small increase in impedance due to effects of the case was observed. This is illustrated in Figure 11 by the slightly higher values of impedance which were measured at increasing distances from the junction of the bond strap and the equipment case. Figure 12 shows the position of the measurement points on the receiver cabinet. These measurements indicate that the case inductance is not a significant factor in establishing the overall bonding impedance, and that the equivalent circuit of Figure 10 adequately represents the impedance to ground at widely separated points on the equipment case.

2.4 Correlation with Radiated Measurements

Although the insertion loss method permits a reasonably accurate measurement of bonding impedance, these impedance measurements in themselves do not necessarily indicate the effectiveness of a bonding strap in reducing the interference caused by case pickup in an EM field. In order to obtain an indication of the relationship between the impedance variations on a cabinet as measured by the insertion loss method and the rf voltages developed at the same point due to an incident field, a series of radiated field tests were made using the setup shown in Figure 13. No attempt was made to generate any specific field strength at any particular point on the cabinet since the basic premise underlying

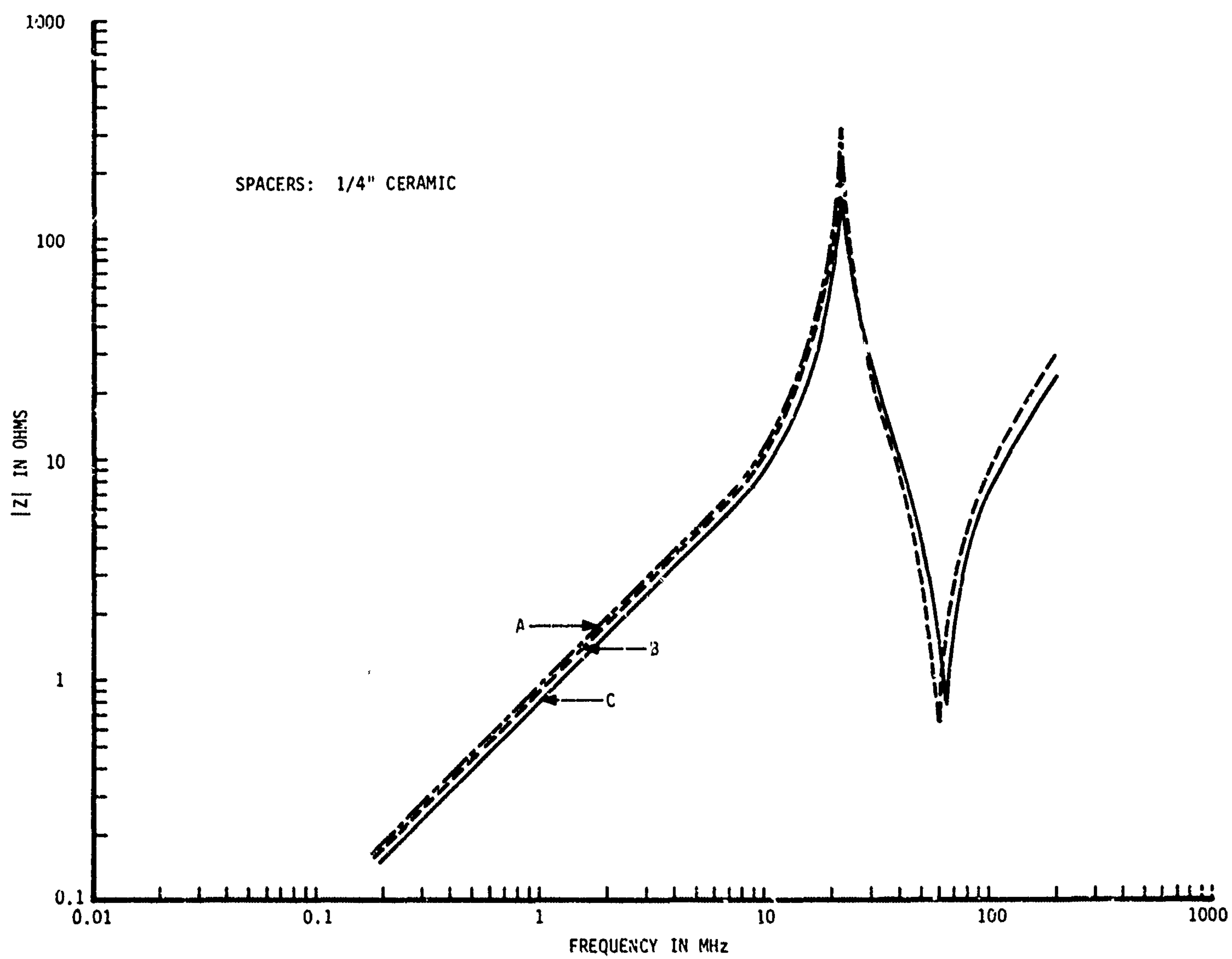


Figure 11. Impedance Variations At Various Points on an Equipment Cabinet.

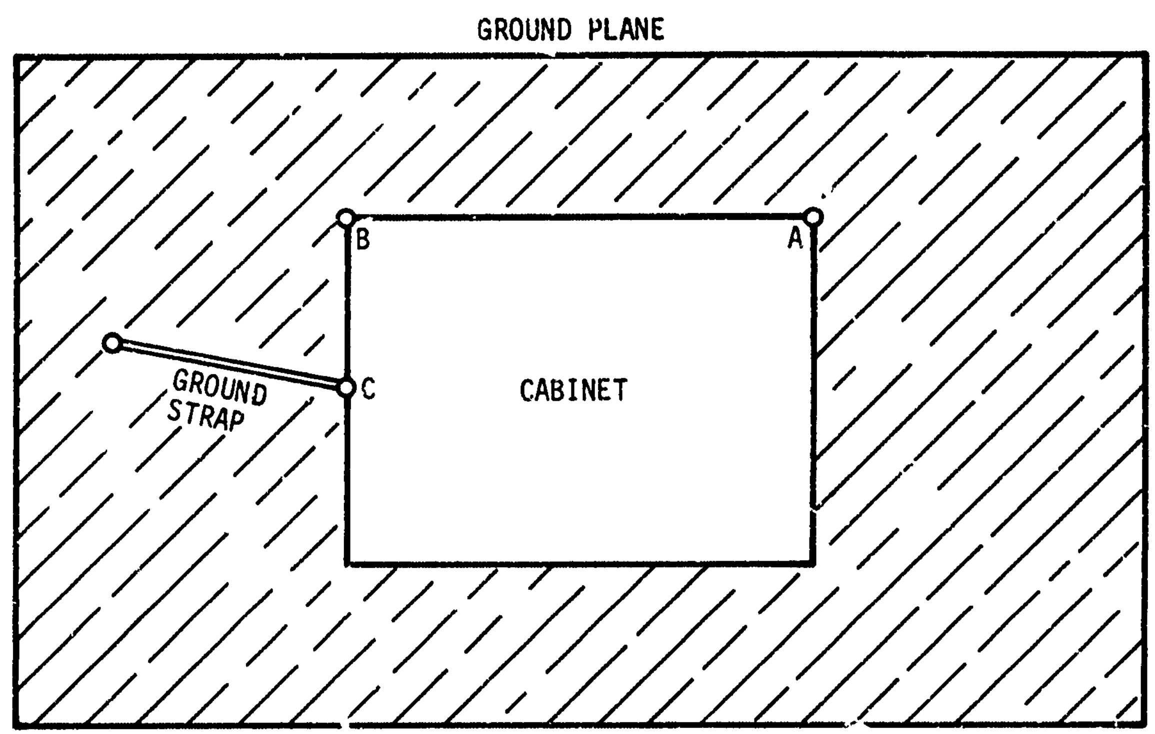


Figure 12. Location of Measurement Points for Figure 11.

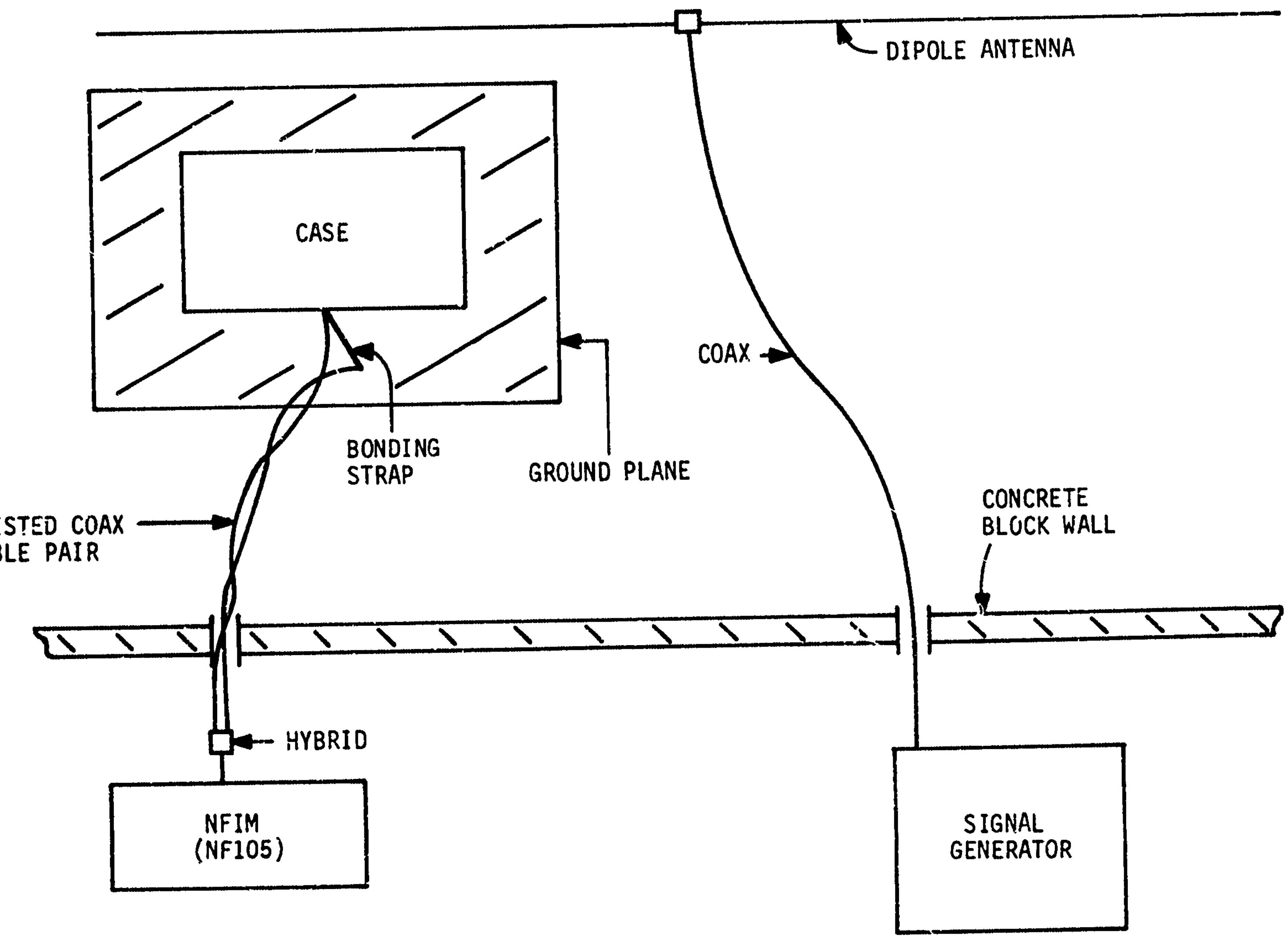


Figure 13. Equipment Layout for Radiated Measurements of Bonding Effectiveness.

these tests was that the effectiveness of a bonding strap should not be influenced by the actual magnitude of the radiated field. Measurements were made of the induced voltage between the equipment case and the ground plane both with and without the bond strap connected. Changes in the induced voltage between the two conditions of strap connected and strap not connected were taken as an indication of the effectiveness of the bonding strap.

An initial problem encountered in the system of Figure 13 was the rf pickup in the cables between the measurement point and the NFIM (The Singer Co., Empire Model NF105) which was, at times, larger than the case pickup being measured. The effect of cable pickup was minimized by using two cables between the measurement point and the NFIM. The center conductor of one cable was attached to the junction of the grounding strap and the receiver cabinet while the center conductor of the other cable was connected to the ground plane. The cable shields were connected together at the ends near the receiver cab. The cables were uniformly twisted and connected to a hybrid junction near the NFIM. Ideally, the voltage appearing at the NFIM should be the difference between the voltage on the center conductors at the desired measurement point. A series of measurements were made over the frequency range of interest to determine the residual voltage appearing at the NFIM due to imperfect cancellation of the cable pickup. The voltages were found to be sufficiently below the levels obtained with the cabinet and strap connected to the measuring leads to insure that no appreciable error was introduced.

Figures 14 and 15 show the effectiveness of two different lengths of bonding straps for different spacings between the cabinet and ground plane. The bond "Effectiveness" indicates the extent of voltage reduction due to the addition of a bonding strap to the cabinet. The negative values mean that the induced voltage was actually greater with the grounding strap connected than with the strap disconnected. The frequencies at which the bonding strap is least effective correspond closely to the frequencies at which the impedance of the case to ground is highest as measured by the insertion loss method. Since the level of induced voltage on equipment cases is directly related to the bonding impedance, the measurement of the bonding impedance between the various equipments in a given installation and the ground plane, or between the several equipments themselves, can be used to give a direct indication of the bonding effectiveness.

2.5 Field Evaluation Techniques

The EMC field engineer who is faced with the problem of evaluating the bonding characteristics of an installation and the design engineer who is trying to estimate bonding requirements need a simple technique to predict the effectiveness of a particular bonding arrangement.

Since the final proof of the effectiveness of any bonding scheme is the extent to which it reduces the potential difference between elements of the system, bonding effectiveness can best be

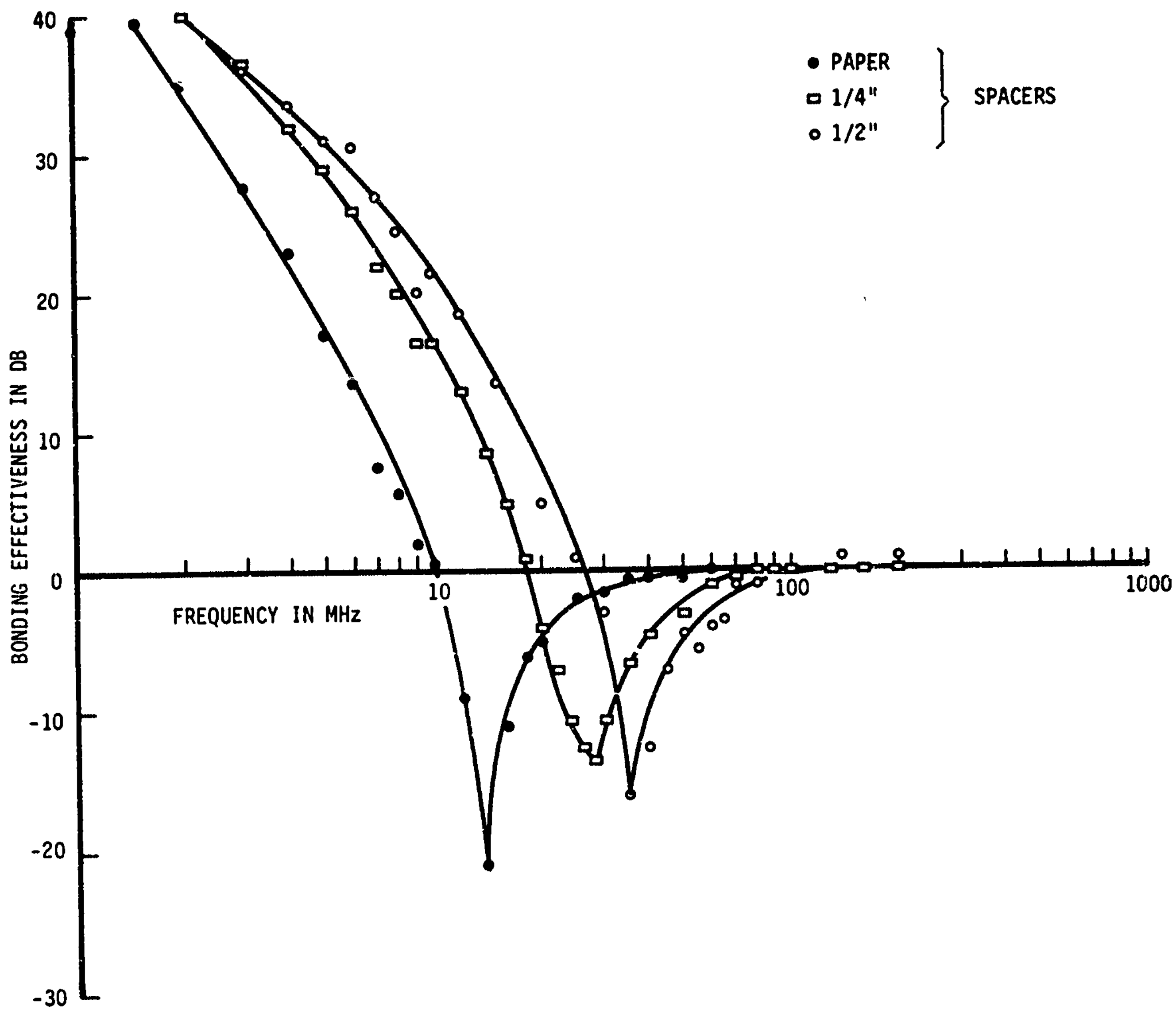


Figure 14. Bonding Effectiveness of a 9-1/2 Inch Bonding Strap.

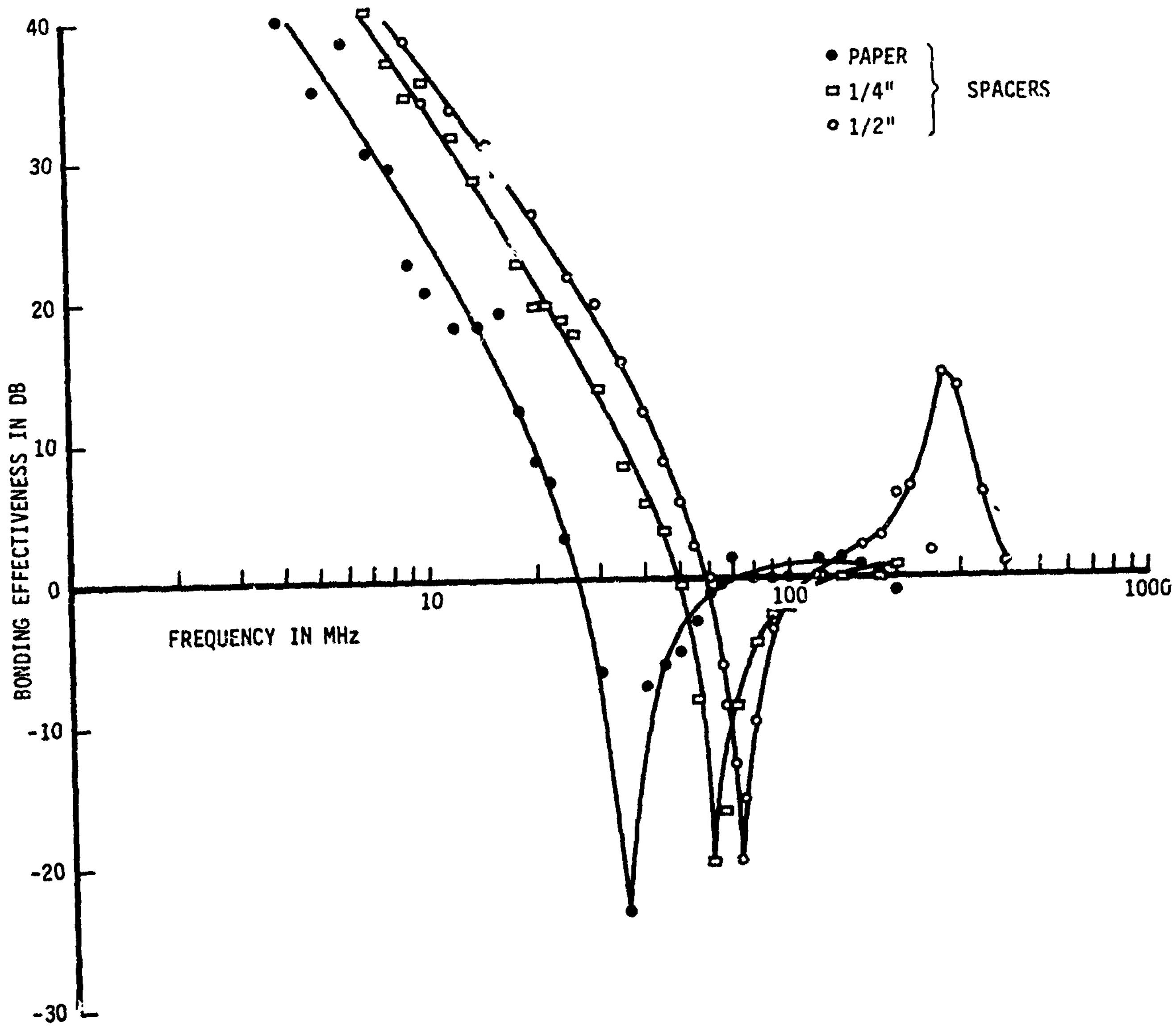


Figure 15. Bonding Effectiveness of a 2-3/8 Inch Bonding Strap.

verified in an actual installation.

An arrangement which permits a rapid evaluation of the bonding impedance in a field installation is shown in the block diagram of Figure 16. The basic technique used is the insertion loss measurement system. With the addition of a sweep frequency signal source and a wideband detector system, the bonding impedance can be plotted automatically over a wide frequency range. The photograph of Figure 17 shows the equipment used in the sweep measuring system. The Telonic model SM 2000 sweep generator and Kay Electric model 1025B amplifier are used in conjunction with the test fixture of Figure 6 and a Tektronix model 561 oscilloscope to give a continuous display of the frequency characteristics of the impedance being tested. The oscilloscope display is especially useful since the continuous display permits changes in the impedance in the bonding system to be observed as they take place. For example, the photographs of Figure 18 show the oscilloscope display of the impedance between the cases of a transmitter and receiver in a rack. The vertical scale is calibrated in ohms and the frequency range of the horizontal axis is approximately 0 to 200 MHz. The frequency markers on the display are spaced 50 MHz apart. Figure 18(a) shows the measured impedance versus frequency with the two equipments tightly bolted in the rack. The addition of a 3 inch long braided strap between the rear of the two cases produces a shift of the impedance peaks to higher frequencies as shown in Figure 18(b).

Figure 18(c) shows the effect of loosening the screws holding the upper case to the rack so that the rear of the upper case makes

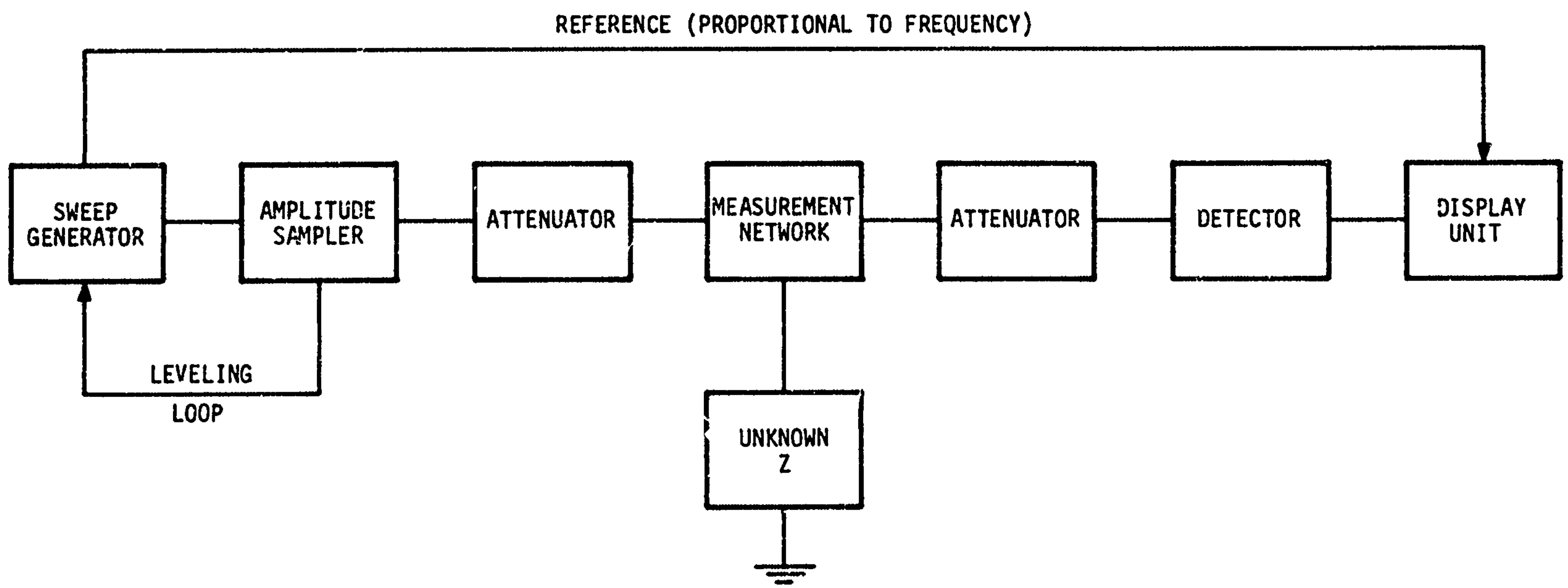


Figure 16. Block Diagram for Sweep Frequency Measurement of Bonding Impedance.

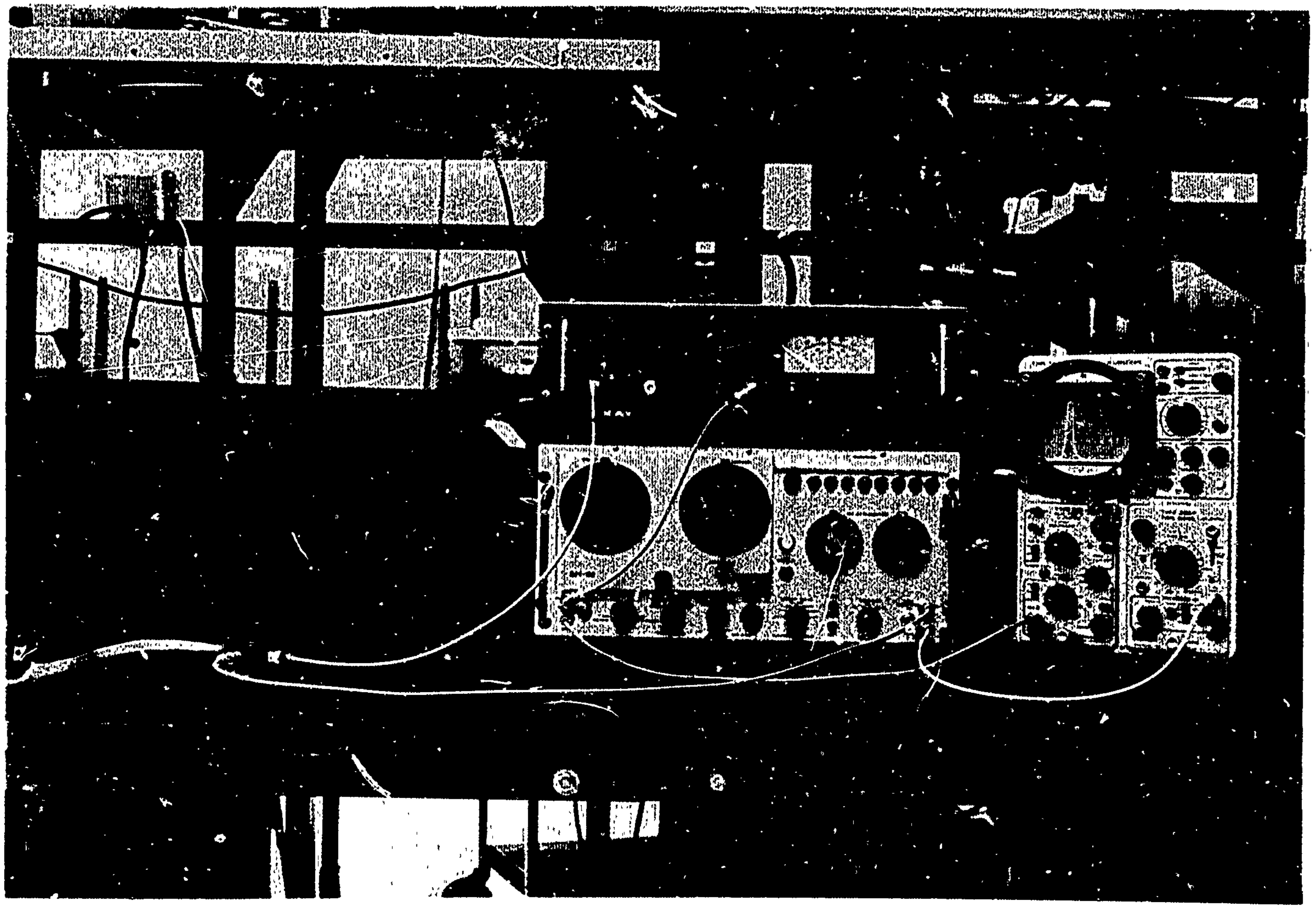


Figure 17. Photograph of Sweep Display Setup.

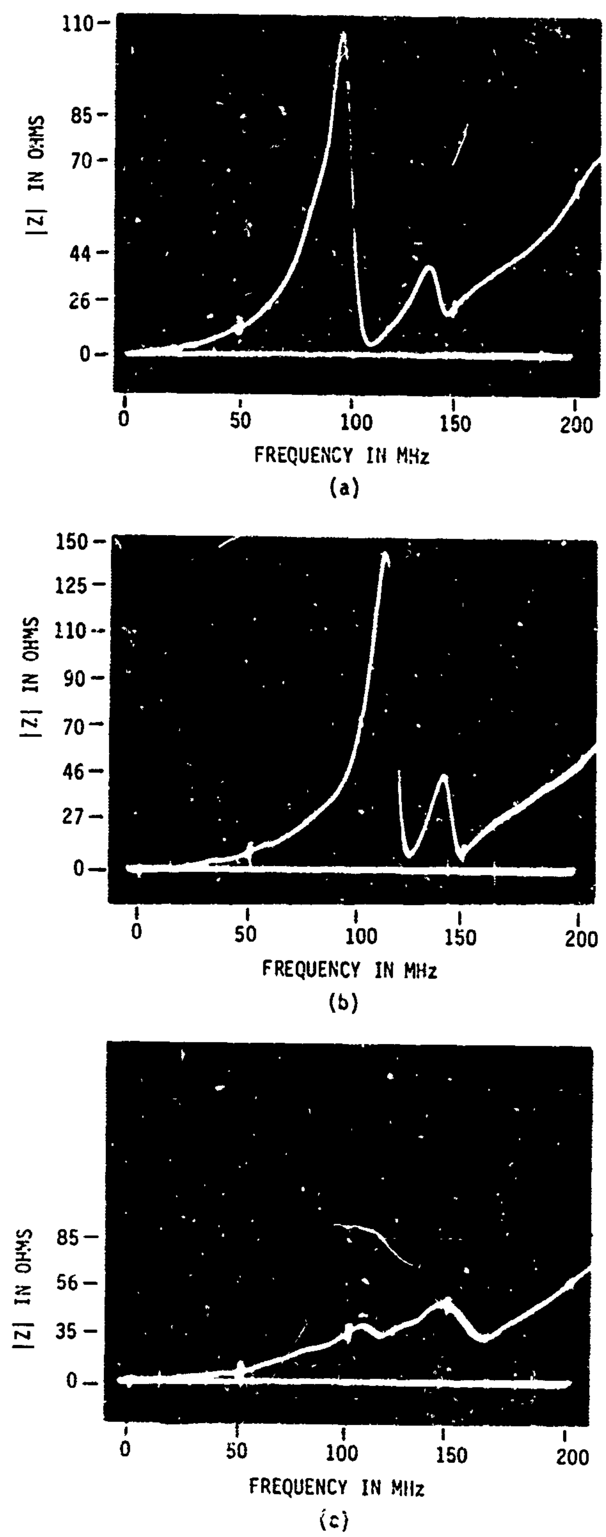


Figure 16. Impedance Characteristics of Rack Mounted Equipment.

a continuous contact with the lower case. The resulting reduction in the magnitude of the impedance points out the possible need of some form of conductive gasket at the rear of the two cases to provide a continuous low inductance connection between them.

The use of the sweep system to display the impedance to ground of the case of an R-361 receiver connected to ground by a 9 inch braided strap is shown in Figure 19(a). The large impedance peak occurs at the parallel resonance of the case to ground capacitance and the bond strap.

The sweep frequency measurement system may also be used to evaluate the performance of individual components over a wide frequency range. For example, the effects of lead inductance on the overall impedance of a typical 1/2 watt resistor in Figure 19(b).

The range over which a capacitor acts as an effective bypass for interfering signals can be quickly determined with the sweep system. Figure 19(c) shows the impedance versus frequency characteristic of a 51 pf capacitor with 1-1/2 inch long leads. The series resonance of the capacitor and its lead inductance occurs at approximately 90 MHz. Above this frequency the reactance of the capacitor increases and its effectiveness as a bypass for interference is impaired.

In some instances the equipment required to make detailed impedance measurements is not available at a field site. In such circumstances an estimate of the resonant frequency of the bond system can be obtained by means of a simple grid dip meter. The meter can be coupled to a bonding strap or other convenient point

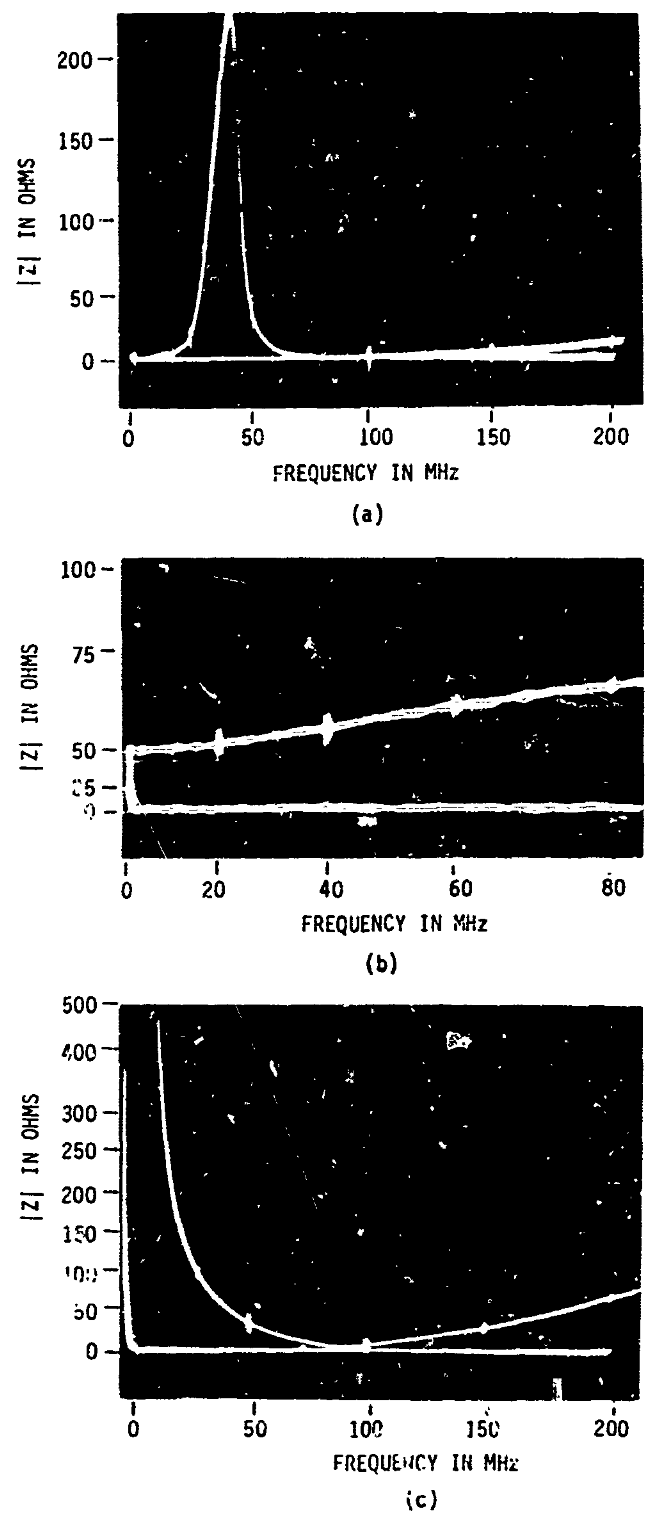


Figure 19. Typical Results Obtained with Sweep Measurement System.

in the system and the resonant frequencies noted. Some idea of the relative impedance magnitudes at the resonant peaks can be gained from the sharpness of the resonance indications on the meter since sharp indications generally correspond to high Q's and, consequently, to high impedances.

If no grid dip meter is available, an estimate of the resonant frequency of the bonding system can be made by calculating the strap inductance from handbook formulas[10] and estimating the capacitance of the system from the dimensions and spacing of the equipments.

Whenever possible an effort should be made to place the resonant frequency of the bonding system as far as possible from the frequencies at which emissions from nearby equipments are known to exist. When no such detailed knowledge is available, a good criterion to use is to make the resonant frequency of the grounding system as high as possible since this condition corresponds, in general, to minimum strap inductance.

2.6 Reduction of Bonding Impedance

It has been established that the reactance of the bonding members and their connecting leads are the primary factors in determining the bond impedance at high frequencies. Consequently, any scheme for reducing the bond impedance must, in effect, reduce the magnitude of this reactance either by modifying the equivalent circuit of the bonding structure or by rearranging the bonding geometry.

2.6.1 Low Pass Filtering

Bonding impedance specifications are usually stated in terms of a maximum permissible impedance that must not be exceeded over some specified frequency range. For example, MIL-B-5087A requires that the bonding impedance must be less than 80 milliohms at all frequencies below 20 MHz.

In general, for a simple bonding strap, the maximum permissible inductance, L_m, which will keep the bonding impedance less than some fixed amount, Z_m, for all frequencies below some specified, f_h, is

$$L_m = \frac{Z_m}{2\pi f_h} \quad . \tag{16}$$

The values given in MIL-B-5087A for Z_m and f_h are $Z_m = 80 \times 10^{-3}\Omega$ and $f_h = 2 \times 10^7$ Hz. Consequently,

$$L_m = \frac{80 \times 10^{-3}}{2\pi \times 2 \times 10^7} = 6.4 \times 10^{-10} \text{ Hy.} \tag{17}$$

For a round conductor, the inductance is related to the physical dimensions by[10]

$$L = 0.00508 \; (2.303 \log_{10} \frac{4\ell}{d} - 1) \; \mu h, \tag{18}$$

where

ℓ is the length in inches, and

d is the diameter in inches.

Assuming a length of 1 inch, the diameter required to meet MIL-B-5087A is 1.3 inches which is an impractical size for most applications. Since the inductance of most practical bond straps far exceeds the value given by (17) it is not generally possible to maintain the bonding impedance within the specifications of MIL-B-5087A. However, by connecting a suitable capacitive reactance in series with the bonding strap, the bonding impedance over some narrow frequency range may be reduced as illustrated in Figure 20. The high impedance of the capacitor at low frequencies makes the use of a series capacitor unacceptable for many applications. A shunting resistor across the capacitor can overcome the difficulty at low frequencies without seriously impairing the high frequency performance. The impedance variation of such an arrangement is shown in Figure 21. Since the reactance of the capacitor is infinite at dc and the reactance of the strap is zero at dc, the low frequency magnitude of the bonding impedance is determined by the value of the shunt resistor. At high frequencies, the capacitor effectively short circuits the resistor and the bonding impedance approximates that of a series LC circuit. The impedance of the RLC network of Figure 21 is

$$Z_B = j\omega L + \frac{R}{1 + j\omega CR} \quad , \qquad (18)$$

which can be expanded to give

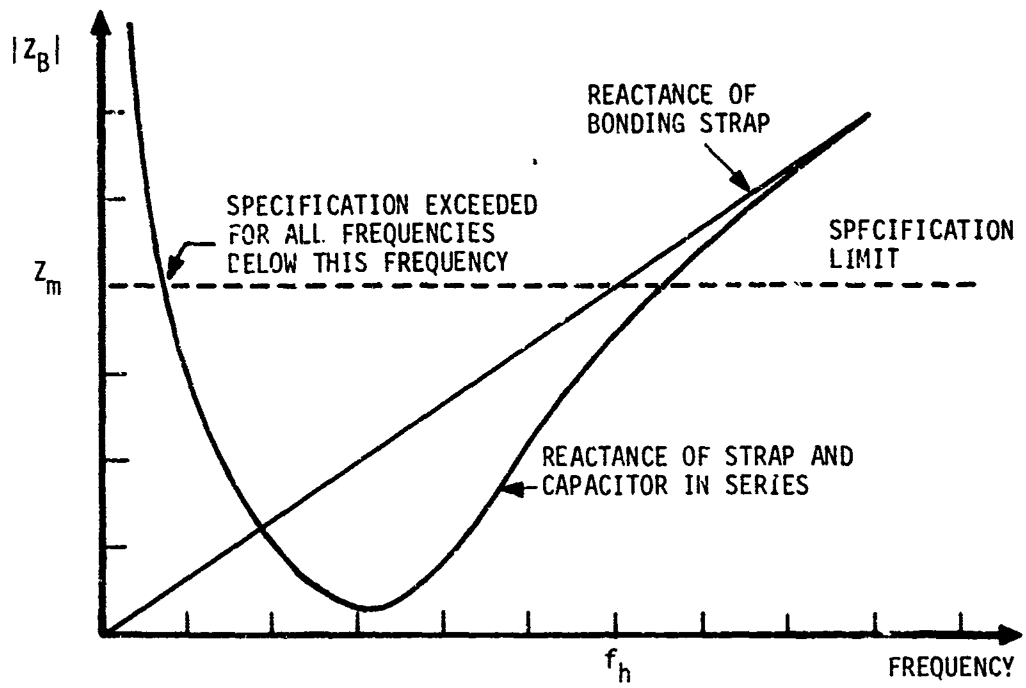


Figure 20. Reactance of a Bonding Strap and Capacitor in Series.

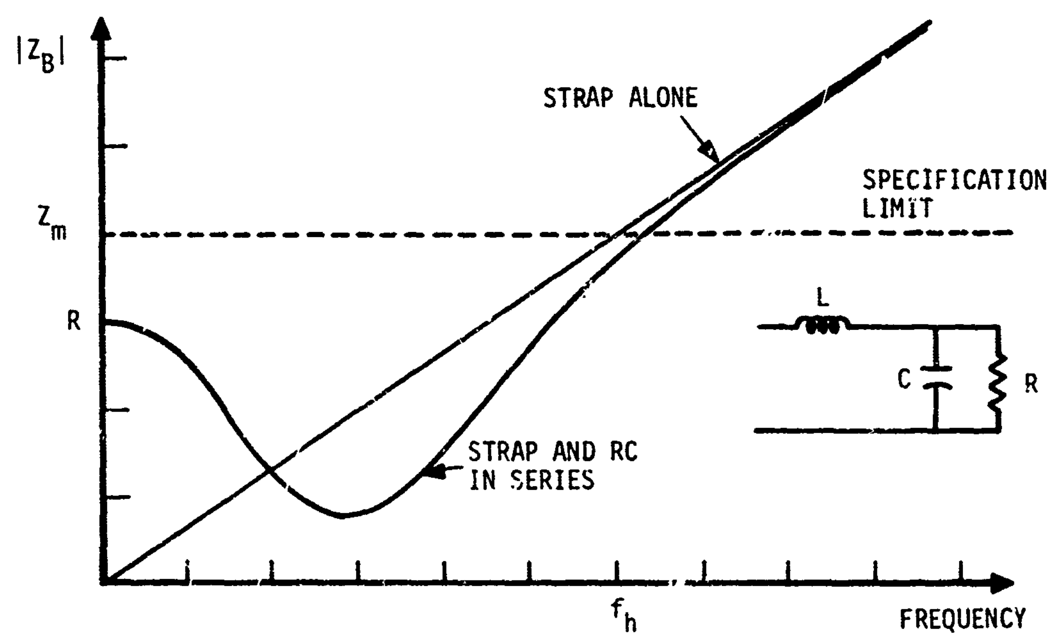


Figure 21. Frequency Behavior of RLC Impedance.

$$Z_B = R \left\{ \frac{1}{1 + \omega^2 C^2 R^2} + j\omega \frac{\left[\left(\frac{L}{R} - CR \right) + \omega^2 LC^2 R \right]}{1 + \omega^2 C^2 R^2} \right\}. \qquad (19)$$

Making the substitutions

$$R = K\sqrt{\frac{L}{C}}$$

and

$$\omega_o = \frac{1}{\sqrt{LC}}$$

gives

$$Z_B = R \left\{ \frac{1}{1 + \frac{K^2 \omega^2}{\omega_o^2}} \right\} \left\{ 1 + jK \left(\frac{\omega}{K^2 \omega_o} - \frac{\omega}{\omega_o} + \frac{\omega^3}{\omega_o^3} \right) \right\} . \qquad (20)$$

In order to meet the specification of a maximum impedance of 80 milliohms at frequencies below 20 MHz, the value of R is chosen to be 80 milliohms. The resulting variation of $|Z_B|$ with increasing frequency as a function of the parameter K is shown in Figure 22. The frequency variation of the reactance of the bonding strap alone (dashed curve) is shown also to facilitate the comparison of the strap reactance with the magnitude of the impedance of the strap and RC network. The curves are shown for four RLC networks, all of which have a lower impedance than that of the strap by itself over significant proportions of the

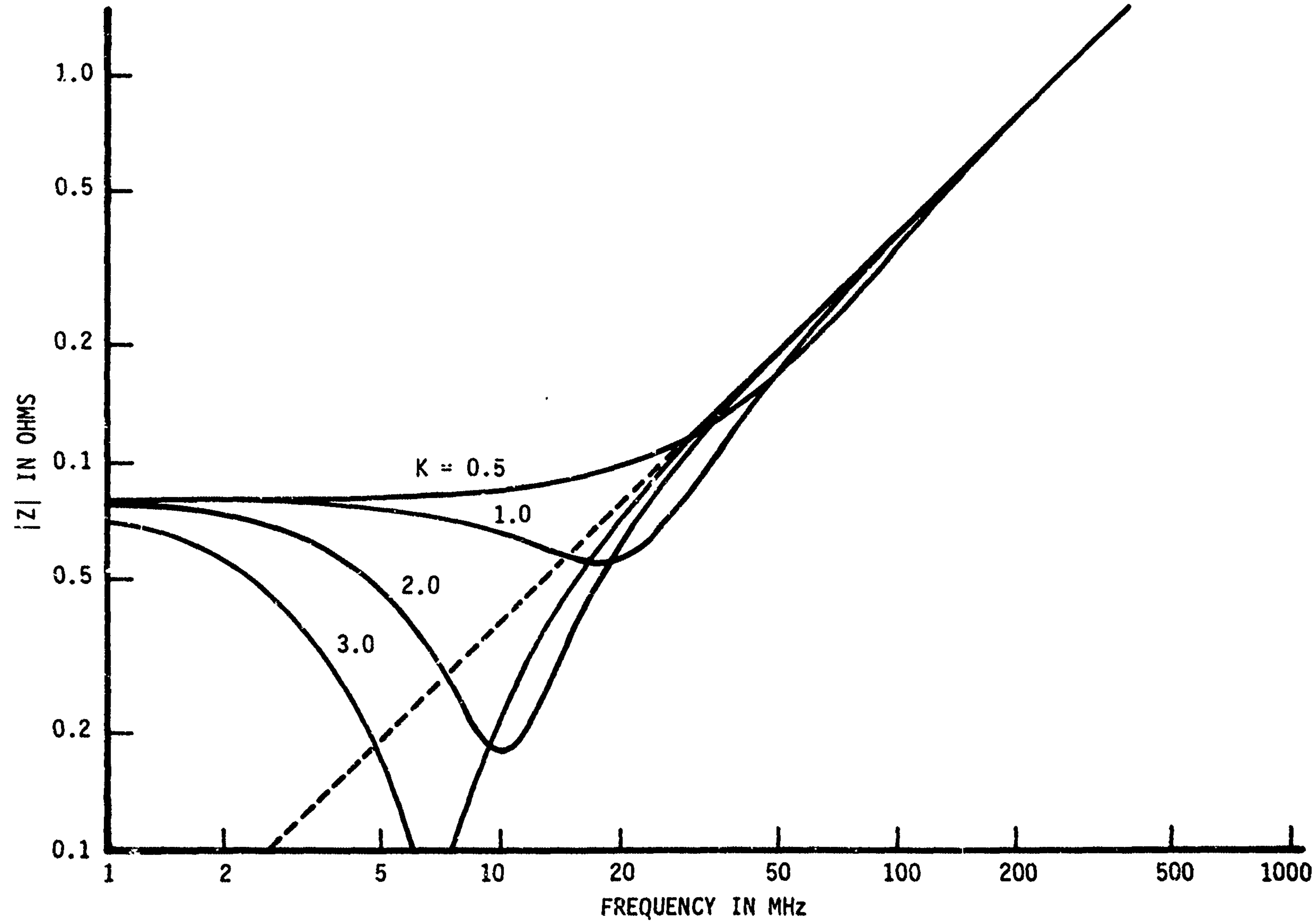


Figure 22. Calculated Impedance Variation of a Constant-K Filter for Various Values of K.

frequency range under 20 MHz. For example, the impedance of the network for K = 3 is lower than that of the strap at all frequencies above approximately 4.5 MHz. An initial laboratory test was made on an actual RLC network to verify the results indicated in Figure 22. The measurements were made on a network consisting of a copper bonding strap 11 in. long and 3/8 in. wide along with an appropriate resistance and capacitance. The component values as well as the results of the measurements are shown in Figure 23. These results are in good agreement with those expected from Equation (20).

When a constant-K filter is placed in the bonding path, the chassis-to-ground capacitance modifies the equivalent bonding circuit in the manner shown in Figure 24. Figure 25 shows the calculated variation in bonding impedance as a function of frequency of the modified circuit for various relative values of the chassis-to-ground capacitance and a constant-K filter of K = 2. Figure 26 shows the measured results of incorporating two different constant-K filter sections into a typical bonding system to reduce the magnitude of the bonding impedance. Curve A illustrates the impedance behavior of the strap between the cabinet and ground plane, while curves B and C show how the performance obtained with the addition of each of the filter sections. The curves indicate that some smoothing of resonance effects can be achieved at the expense of a higher dc impedance level, i.e., larger R.

An effort was made to reduce any strap inductance associated with the R and C used in obtaining the data of Figure 26 by constructing

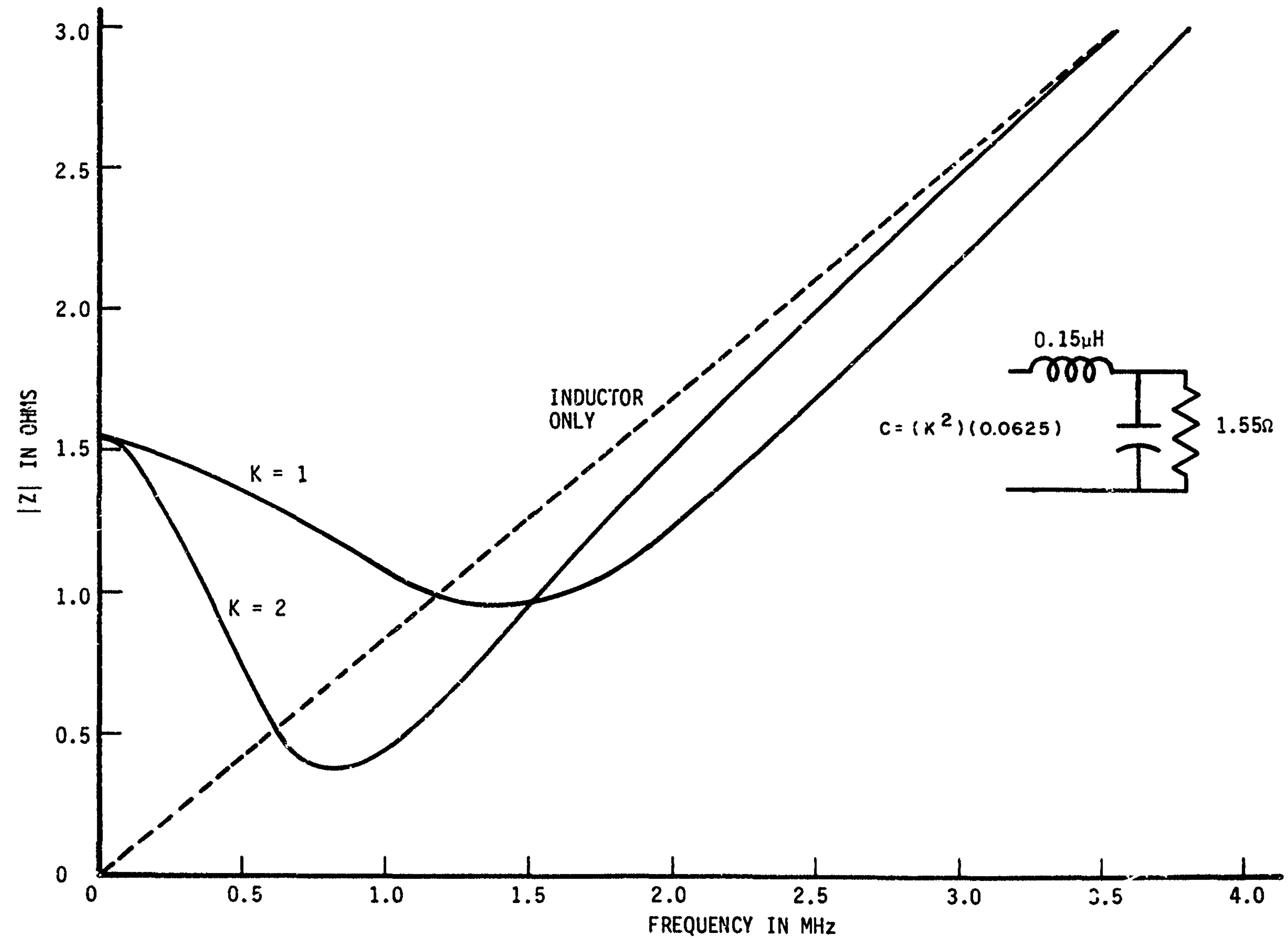
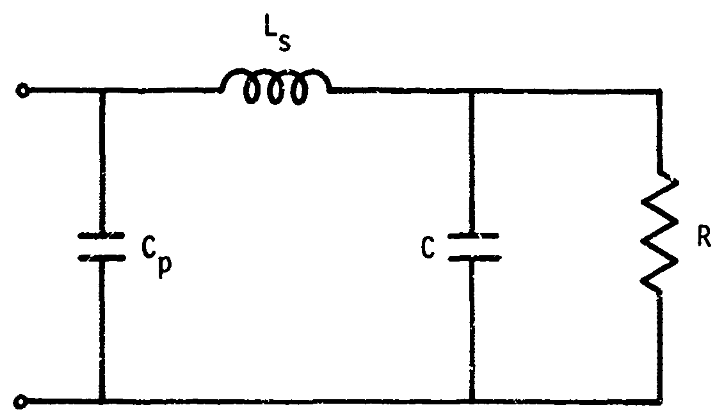


Figure 23. Measured Variation of Bonding Impedance for a Constant-K Filter.



L_s: BONDING STRAP INDUCTANCE

C_p: CHASSIS-TO-GROUND SHUNT CAPACITY

R,C: ELEMENTS OF CONSTANT-K FILTER

Figure 2[illegible]. Equivalent Circuit of the Constant-K Bonding Filter Including the Shunt Capacity from Case to Ground.

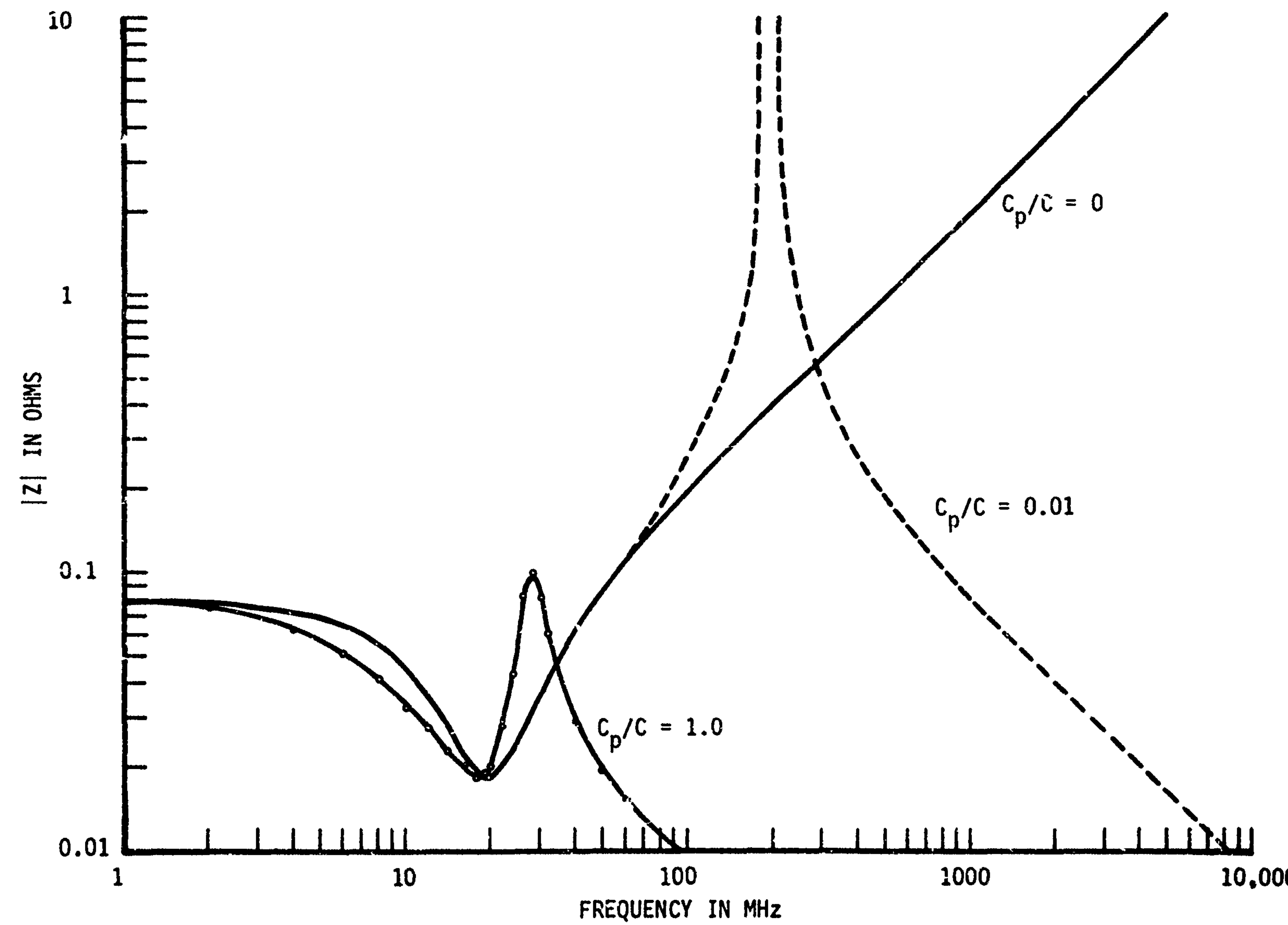


Figure 25. Calculated Variations of Bonding Impedance for Various Relative Values of Shunt Capacity.

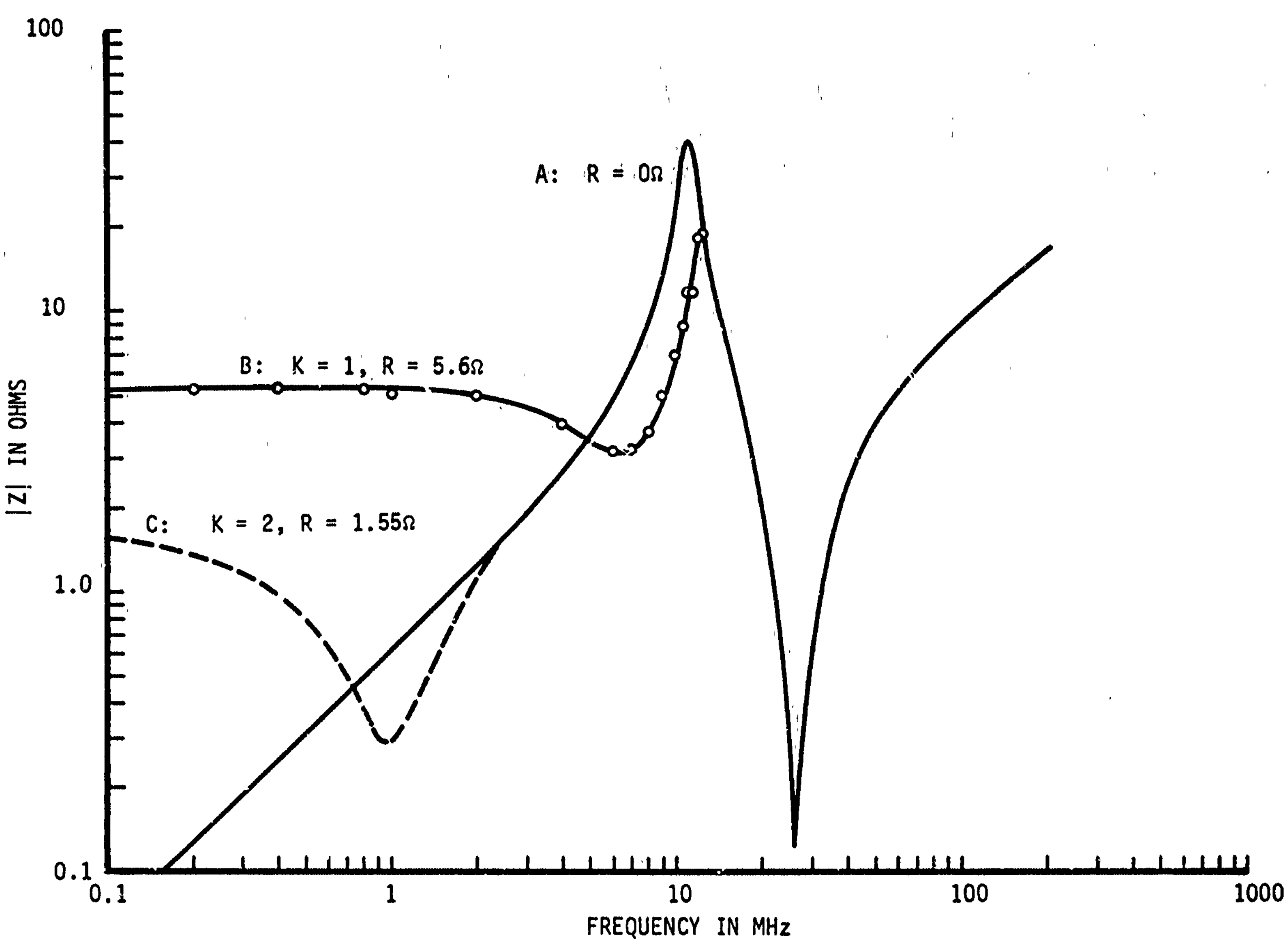


Figure 26. Measured Impedance Variations for Three Bonding Arrangements.

a capacitor which had distributed shunt resistance incorporated into the structure of the capacitor. The capacitor was constructed by sandwiching a thin sheet of dielectric between a rectangular conducting plate and the ground plane. The size of the rectangular capacitance plate was selected to give a capacitance which was equal to the capacitance between the cabinet and ground plane. The distributed resistance was realized by painting along the edge of the capacitor with a resistive material consisting of a colloidal suspension of conducting particles. The bonding strap was attached to the top plate of the capacitor. In Figure 27, the normal resonance curve for the strap inductance and shunt capacitance between case and ground is shown. First, a commercial resistor of 33 ohms was placed in parallel with the laboratory-constructed capacitor. Then this resistor was replaced with one made as described above. The results were similar for both resistors. Next a custom made resistor of smaller resistance was evaluated. The impedance level at low frequencies decreased and the resonant peak was at about the same impedance maximum as for the 33 ohm resistors. The results are quite similar to those of Figure 26 and indicate that the use of laboratory constructed R and C elements gives no substantial advantage over the use of commercial components.

From Figure 25, the ratio $C_p/C = 1.0$ appears to be the minimum necessary to provide the most uniform bonding impedance over the frequency range up to 20 MHz. Table I summarizes the various values of resistance, inductance and capacitance that are necessary to meet the requirements of a constant-K filter and a ratio $C_p/C = 1.0$, simultaneously.

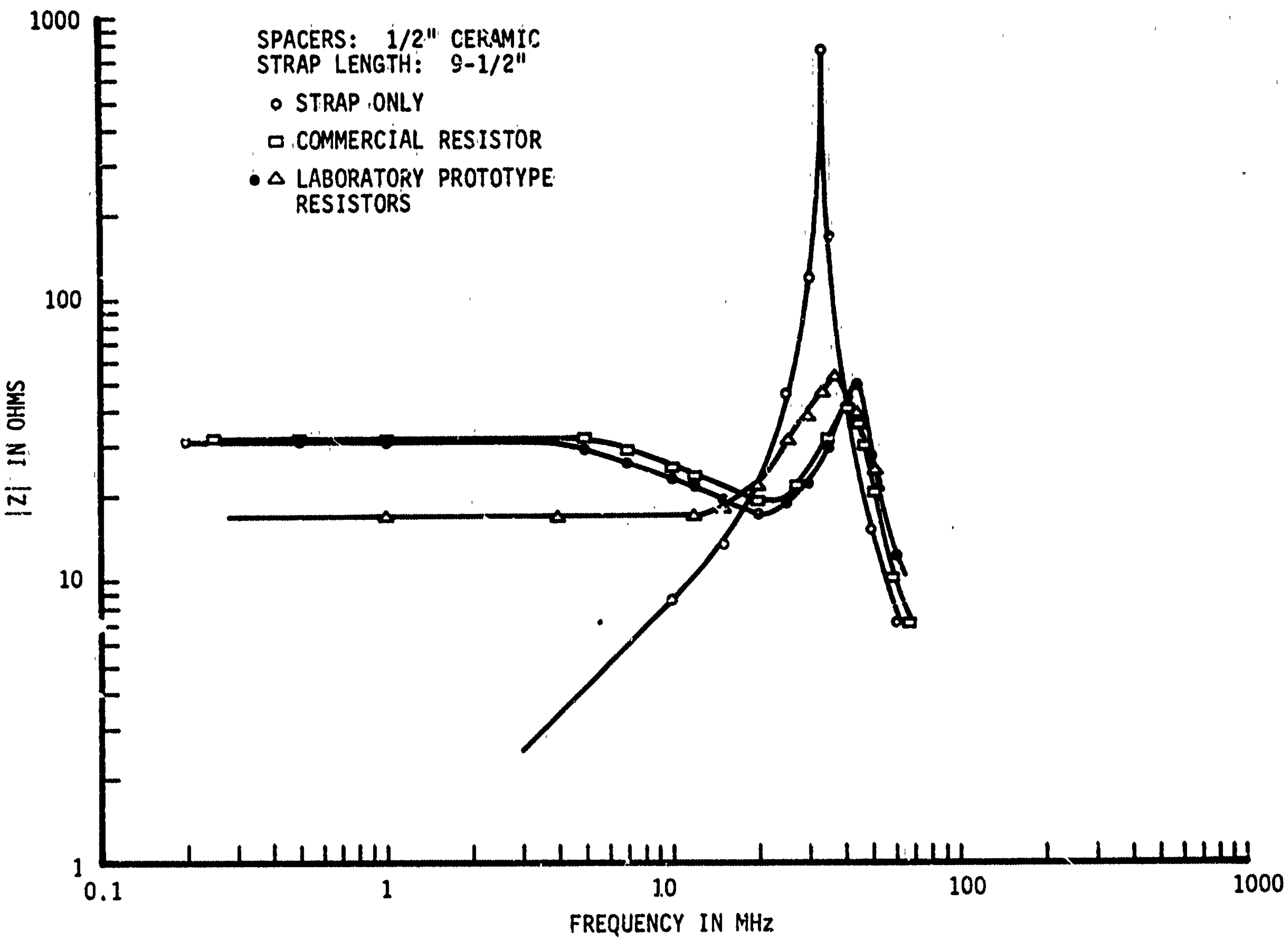


Figure 27. Impedance Variations of Laboratory Model of Bonding Filter.

TABLE I

COMPONENT VALUES FOR CONSTANT-K FILTER FOR $C_p/C = 1.0$

K	Resistance in ohms	Long Strap ($\ell \approx 10"$) $L = 1.5 \times 10^{-7}$ H.	Short Strap ($\ell \approx 1"$) $L = 1.5 \times 10^{-8}$ H.
1	R = 0.08*	C = 23.4 µF	2.34 µF
1	R = 27.4	C = 200 pF+	
2	R = 55.8	C = 200 pF	
1	R = 19.4	C = 400 pF++	
2	R = 38.8	C = 400 pF	
1	R = 8.66		C = 200 pF
1	R = 6.12		C = 400 pF

*Impedance level specified by MIL-B-5087A.

+For spacing between R-361 receiver case and ground plane of 1/4 inches.

++R-361 receiver case separated from ground plane by 1/2 inch spacers.

Selected values of inductance and capacitance which are representative of practical situations are examined. The resistance and capacitance values tabulated in Table I emphasize the practical boundaries which limit the incorporation of a typical bonding strap into a constant-K filter. If the specified maximum dc resistance level of MIL-B-5087A is satisfied, then unrealistic capacitance values are required. If typical capacitance values are utilized, then higher impedance levels result.

Other filter configurations, such as a three-pole Butterworth, also result in similar conflicts between reasonable component values and large impedance levels. For example, Figure 28 shows two Butterworth filters: one is designed on the basis of an 80 milliohm impedance level; and the other is designed around a typical chassis-to-ground capacitance. Each filter has a 20 MHz cutoff frequency. As in the case of the constant-K filter practical values of capacitance are obtained only when the impedance level of the filter is high with respect to 80 milliohms. Consequently, the practical application of the filter technique is limited.

2.6.2 Conductor Length Reduction

One logical step for minimizing the bonding impedance between two members is to make the bonding connection as short as possible. The limits of this approach are attained when the members are in metal-to-metal contact assured by welding or another similar bonding scheme. Nevertheless, even very short bonding paths between members of the bonding system can often result in impedances which fail to meet the specifications of MIL-B-5087A. To illustrate this point, the cabinet of a receiver, R-361/GR, was supported on 8-32 screws at 3/8 in. and 1/2 in. above the ground plane. Figure 29 shows the impedance levels measured under both circumstances. The minimum impedance at 20 MHz is 2 ohms. A long strap, 9-1/2 in. in length, was attached between the cabinet and ground plane with no difference noted in the impedance.

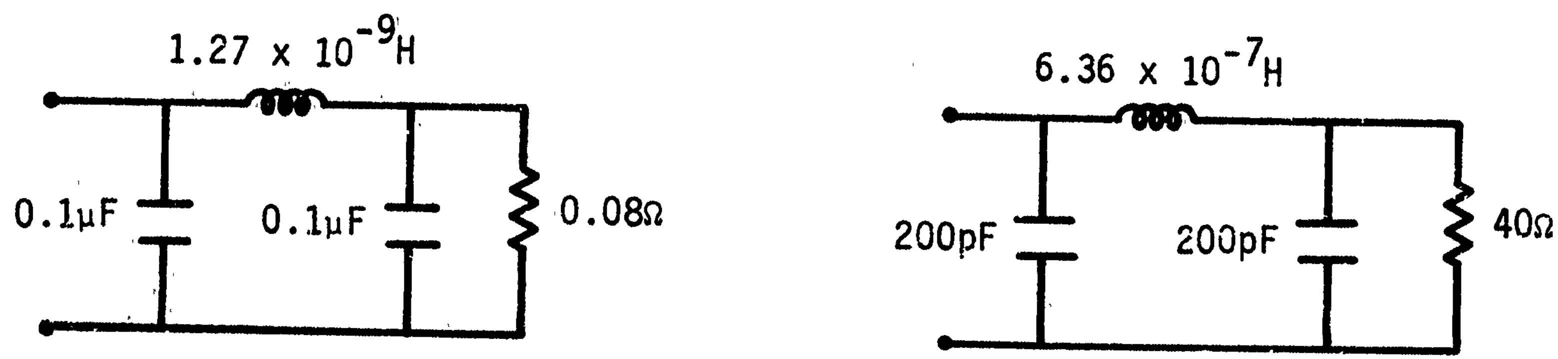


Figure 28. Two Butterworth Filters Designed for a 20 MHz Cutoff Frequency.

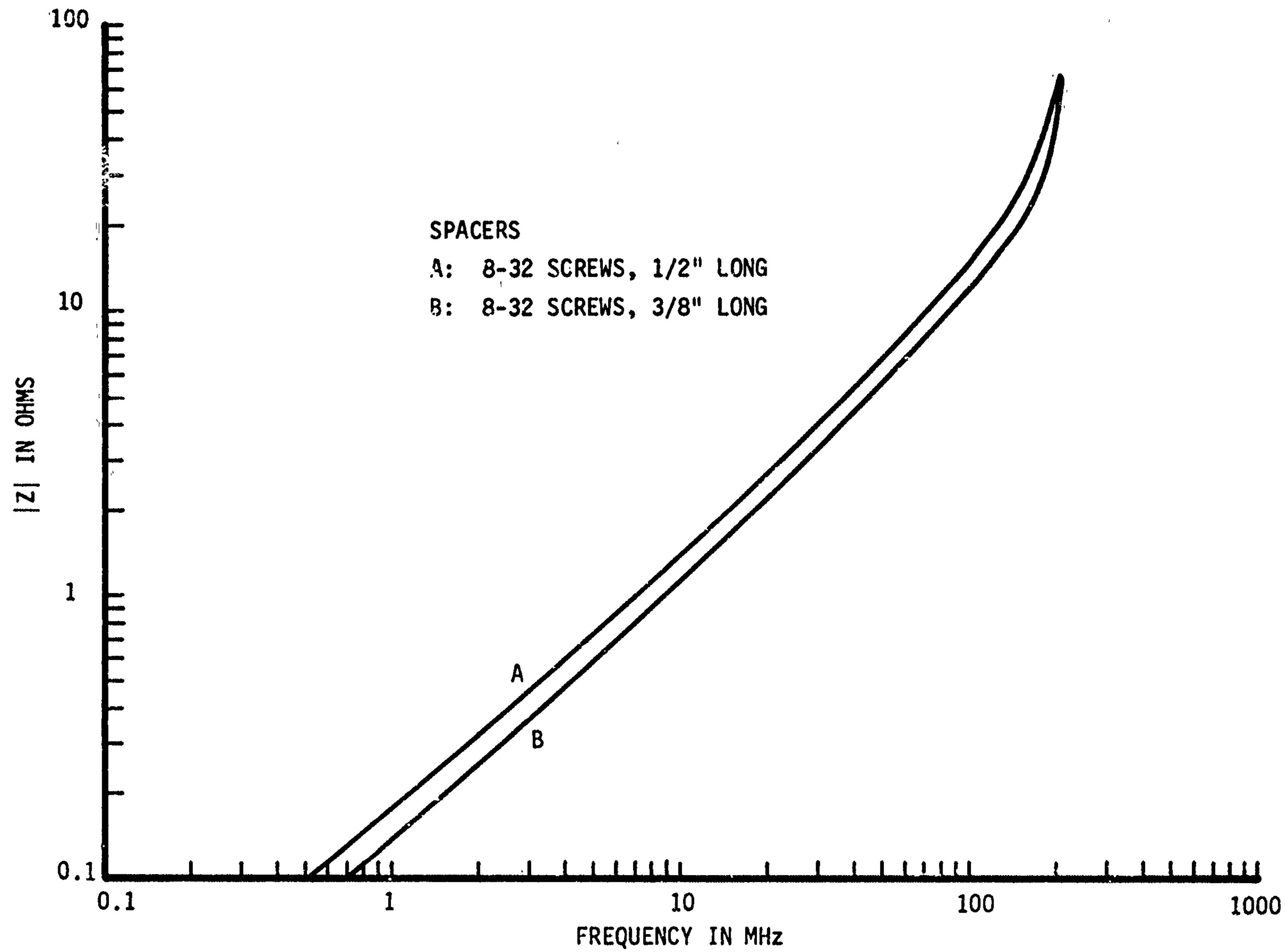


Figure 29. Bonding Impedance Variations for Two Sets of Short Bonding Connections.

2.6.3 Conductor Paralleling

Another direct means of reducing the inductance of the bonding path is by using several straps in parallel. The effects of additional bonding straps in parallel were examined by separating the cabinet and ground plane with 1/4 in. ceramic spacers. Several lengths of bond strap in parallel were used to connect the cabinet to the ground plane. Figure 30 shows that the impedance at a particular frequency can be reduced by increasing the number of parallel paths to ground but that the large peak of impedance is still present. In many instances, the maintenance of the impedance peak after adding additional straps in parallel may be quite acceptable since the parallel resonant frequency of the case capacitance and the bonding inductance can be shifted to a frequency range where the impedance peak is not objectionable.

2.6.4 Resonant Impedance Reduction

In practical installations, situations will arise in which the optimum adjustment of inductance and capacitance between members of the system will not be possible. In view of this expectation, investigation was directed into the possibilities of decreasing the parallel resonant impedance by degrading the Q of the bonding conductor, the case-to-case capacitance, or both. As a first step, the bonding strap was given a lossy coating of collodial solution of graphite which is sold under the trade name of Aquadag.*

* Acheson Colloids Company, Port Huron, Michigan

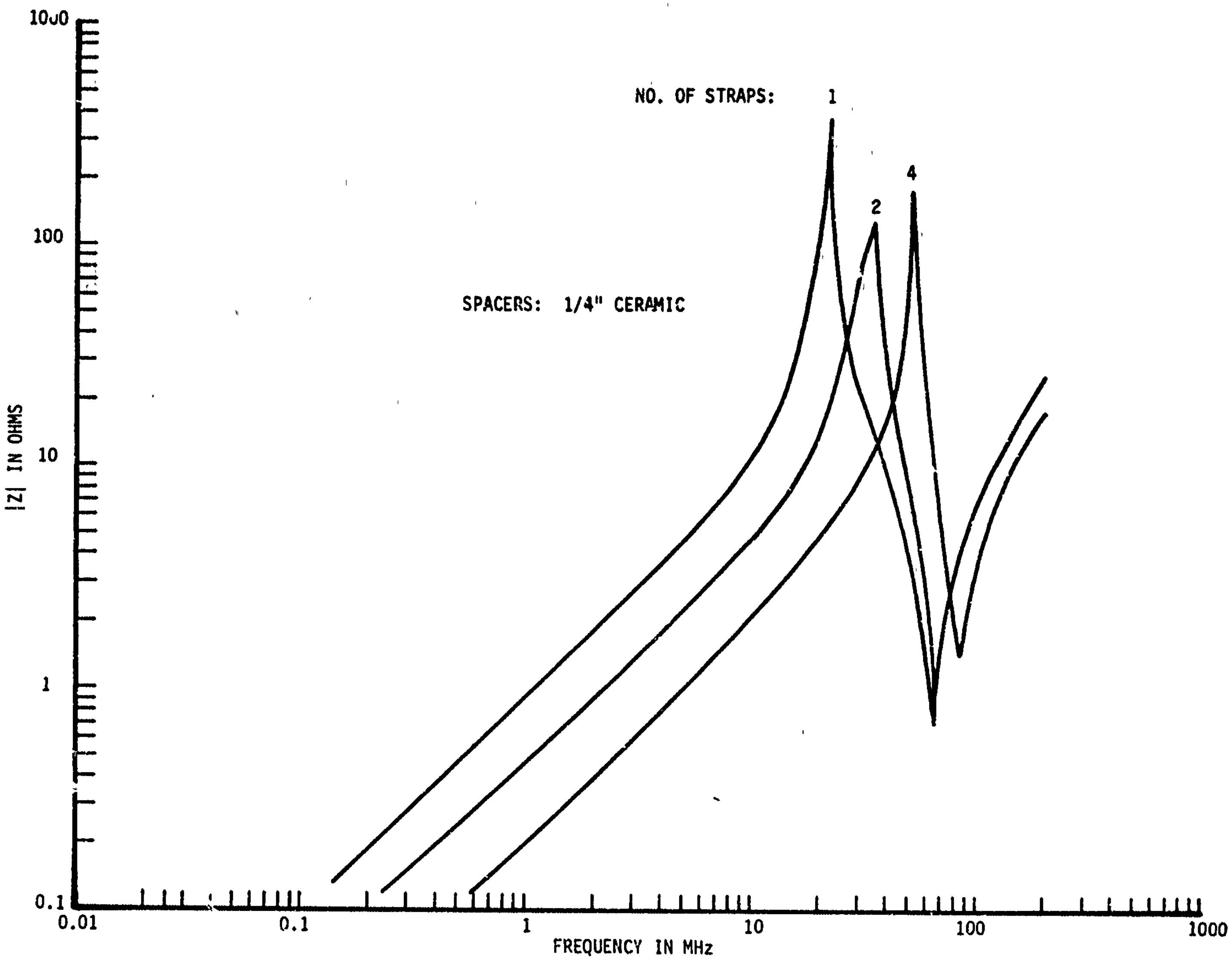


Figure 30. The Effects of Increasing the Number of Conducting Straps on the Bonding Impedance.

Next, the bottom of the cabinet was given a coating. Finally, the ground plane was coated in the area beneath the cabinet. Figure 31 shows the impedance values which were measured following each of these steps. The lossy coating does lower the Q, but the extent of the reduction is not sufficient to be useful. A direct method to reduce the Q of the resonant circuit is the insertion of a resistance in series with the strap. The effect of adding a 22 ohm resistor in series with the strap is evident in Figure 32.

2.6.5 Active Devices

The use of an active device to produce a negative inductance which could be used to effectively cancel the inductance associated with the bonding strap was investigated. A short circuit stable device which was inserted in series with an inductance worked well enough to verify the approach but only at impedance levels higher than those desired in a bonding network. The principle obstacle at the present time is the realization of an active device whose inherent impedance is low enough to permit the cancellation of reactances as small as those associated with a conventional bonding strap.

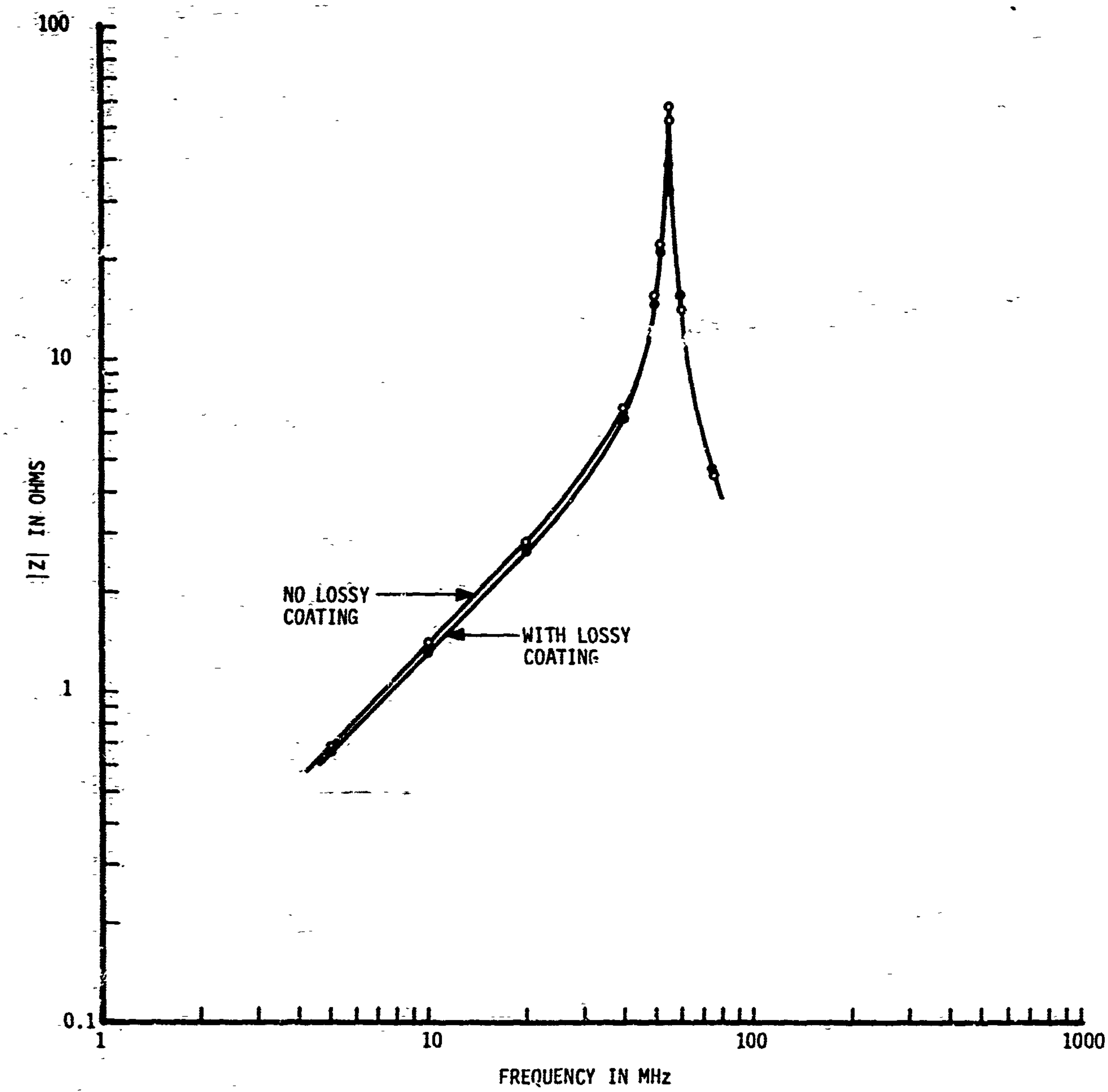


Figure 31. The Effects of Lossy Coatings on Bonding Impedance.

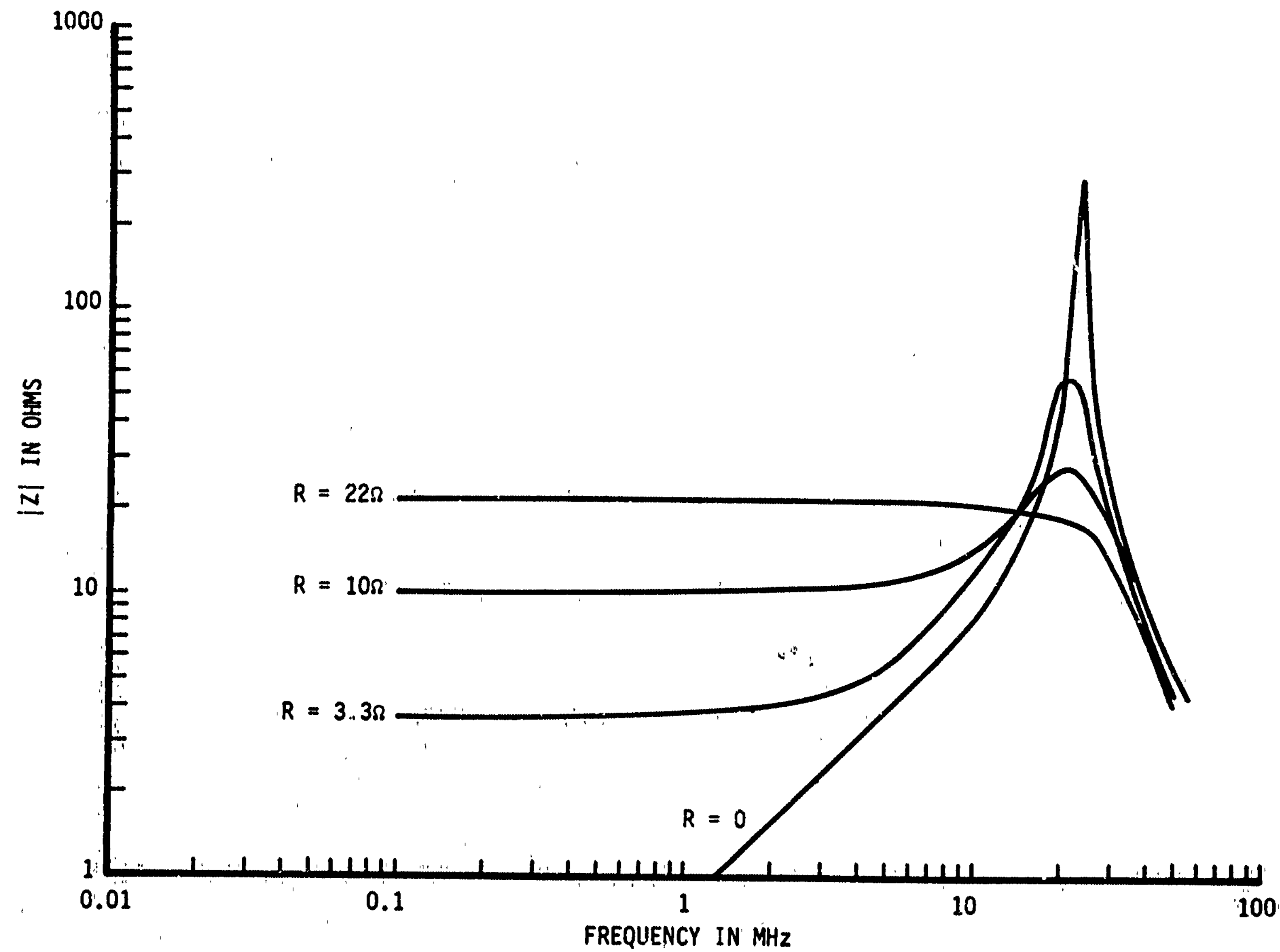


Figure 32. The Effects of a Series Resistance on the Bonding Impedance.

3. Conclusions and Recommendations

When equipments are tied together by a bonding structure in an effort to place them in a common rf potential, the bonding impedance between these equipments at high frequencies is determined primarily by the reactance of the bonding structure. The inductive reactance exhibited by such structures can parallel resonate with stray capacitances associated with the equipments being bonded to produce large peaks in the magnitude of the bonding impedance. These peaks can often occur in the lower portions of the hf range.

The results of radiated susceptibility measurements have shown that good correlation exists between the frequency locations and magnitudes of these impedance peaks and the frequency locations and magnitudes of the maxima in the induced rf voltages due to incident fields on equipment structures.

The magnitude of bonding impedances can be accurately determined by the use of an insertion loss method. Using commercially available equipment in conjunction with simple test fixtures, the insertion loss measurement can be readily adapted to a sweep frequency technique which gives a continuous visual display of bonding impedance over a wide frequency range. The simplicity of the measurement procedure permits use of the technique under either laboratory or field conditions. A particularly desirable feature of the system is that the effects of a modification of a bonding configuration are immediately evident and do not require extensive personnel time. For example, the engineer who is trying to improve a bond strap network to reduce case related interference can see the effects of changes as they are made. The engineer can, therefore, devote more of his time to corrective action rather than to meticulous and time consuming point-by-point measurements. The system is also adaptable to the evaluation of components, such as resistors and capacitors, in terms of their rf impedance behavior.

When measurements of the bonding impedance magnitudes in an equipment installation have shown these impedances to be unacceptably high, several techniques are available which can reduce or modify the impedance variation with frequency in such a manner that, in the frequency ranges where interfering signals occur, a reduction in impedance is obtained. These techniques include resonating bonding straps with series capacitors, incorporating the reactance of bond straps in low pass structures, the use of multiple straps in parallel and the use of series resistance with a bond strap to lower their Q. In general, the most effective method is the use of parallel straps since this method lowers the overall inductance of the bonding structure. However, this lower inductance can, in some instances, shift the frequency position of an impedance peak to an undesired location. Consequently, the effect of additional straps, as well as the application of any other impedance reduction technique, should be evaluated over the entire frequency range of interest to determine its true effectiveness. Such evaluations can easily be made with the sweep frequency insertion loss measuring equipment.

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13. ABSTRACT

The significant factors affecting bonding impedance at high frequencies are examined and the reactance of the bonding structure is shown to be the major contributor. Resonant effects caused by stray capacitances are examined and an equivalent circuit is presented to explain the experimentally observed variation with frequency of the bonding impedance.

Several techniques for the reduction of bonding impedance are described and experimentally evaluated.

A technique for continuous visual display of bonding impedance versus frequency is presented and its suitability for field use is noted.

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