COMPARISON OF THE ELECTROMAGNETIC SHIELDING PROVIDED BY CIRCULAR AND RECTANGULAR CONNECTORS AND THEIR ACCESSORIES

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ABSTRACT

Comparison of the transfer impedance measurements of circular and rectangular connectors show that the shielding performance of rectangular connectors can approach that of circular connectors if supplemental contacts, such finger stock or "dimples," are used to ensure circumferential contact between the plug and receptacle. In addition, quality backshells and circumferential braid terminations must be used in order to achieve optimum shielding performance. Contact impedance is the principal coupling mechanism in circular connectors and usually dominant in rectangular connectors. The high frequency coupling of most connectors is usually equivalent to that through a few inches of single braid. Aperture coupling in the connector is relatively unimportant.

INTRODUCTION

The transfer impedance of most circular connectors is generally low since the interface between the connector and the backshell is usually threaded and constructed in accordance with an appropriate military standard. Thus, they provide good electromagnetic shielding. The connector/backshell interface of rectangular connectors, on the other hand, is usually less well defined. Thus, circular connectors are generally used in critical applications that require good electromagnetic shielding. In practice, it is the interfaces between the various interconnection components that usually determine the overall quality of an EMI shielded cable assembly. Each of these interfaces is a potential coupling path by which electromagnetic energy can pass through the shield.

Both circular and rectangular connectors must have a backshell or other accessory that mates the connector to the cable shield. While the interface between the connector and the backshell must be different in the case of circular and rectangular connectors, the interface between the backshell and the cable shield, usually metallic braid, often is the same for both kinds of connectors. It can take on many forms, being limited only by the imagination of the backshell designer for producing a product that has good electromagnetic characteristics, is easy to use, maintains its integrity during its lifetime, and is economical to manufacture. Typical designs for the backshell-to-braid interface include a variety of dual cones, a large screw thread, a circular coil spring, metal bands, and various permanent assembly techniques such as a swaged ring, solder and an electromagnetically compressed ring.

The intrinsic electromagnetic property of the shielded cable assembly is its surface transfer impedance, which relates the longitudinal voltage inside of the shield to the current on the outside [1]. The concept of surface transfer impedance is applicable to connectors, backshells, and cable terminations as well as to cables and cable assemblies. At low frequencies, usually

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below a megahertz, the transfer impedance of the connector and its accessories is determined by current diffusion and contact impedance across each interface. In this frequency range, the surface transfer impedance is equal to the component's d.c. resistance.

In cable shields at the higher frequencies (above a megahertz), the surface transfer impedance can generally be represented by a mutual inductance that is determined by apertures in the shield or by porpoising. If the mutual inductance due to aperture and/or porpoising coupling is small, as would be the case in a connector or backshell, the contact impedance between the parts of the cable assembly can become the dominant high frequency coupling mechanism. This is particularly true because contact impedance is proportional to the square root of frequency (increasing at 10 dB/decade) at the higher frequencies.

After briefly discussing surface transfer impedance measurement techniques, this paper will present the measured transfer impedance of a number of types of braid terminations since these are often used for both circular and rectangular connectors. Next, circular connectors will be discussed. In particular, this paper will summarize a series of measurements of the surface transfer impedance of special samples that incorporated the features of eight military and commercial backshell/connector interfaces. These measurements will then be compared with the total surface transfer impedance of a connector plug/receptacle (with backshell and braid) in order to determine the relative contribution of each element. Next, transfer impedance measurements of rectangular connectors will be summarized. Speciffically, measurements made on shielded DB-25 and EMI versions of rack-and-panel connectors will be presented. Finally, the measured transfer impedance of rectangular connectors will be compared to each other.

MEASUREMENT PROCEDURES

For a connector, surface transfer impedance is defined as the ratio of the voltage induced on the inside of the connector/backshell assembly divided by the current flowing on the outside of the shield. Note that the connector is considered a point coupling source. Therefore it is a simple impedance with units of Ohms (Ω) as different from a shielded cable which is a distributed source with units of Ohms/meter (Ω/m).

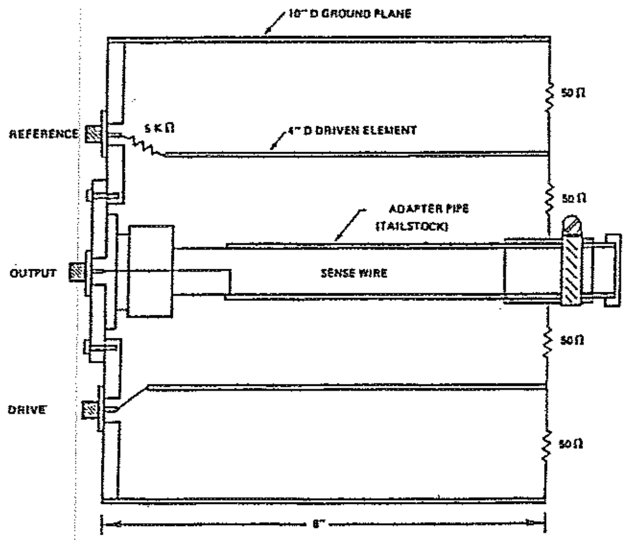

Figure 1. Diagrammatic View of the Quadraxial Connector/Backshell Test Fixture.

The surface transfer impedance of most of the samples reported in this paper was measured using the short quadraxial test fixture shown in Figure 1 and one or more network analyzers controlled by a computer via an IEEE-488 bus. An HP-461A signal amplifier and an IFI 5300 were used to optimize the signal-to-noise ratio when low level measurements were made.

The quadraxial test fixture had previously been calibrated using a set of copper and stainless steel calibration samples. The present test series included an instrument calibration sample consisting

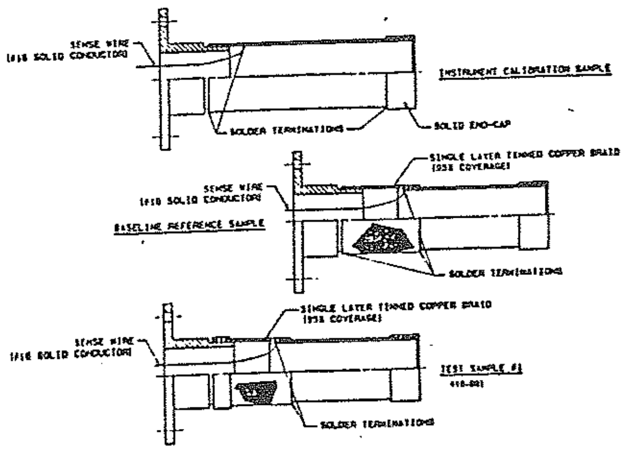

Figure 2. Instrument Calibration, Reference, and Swaged Braid Samples.

of a solid copper pipe soldered to a nickel-plated aluminum adapter. The measured surface transfer impedance of this sample is shown in Figure 2 [2,3,4]. Below 100 kHz, the surface transfer impedance showed the typical behavior expected of a solid shield. Above 100 kHz, the transfer impedance was below the noise floor of the measurement system. The data shown in Figure 2 demonstrate that the equivalent transfer impedance of this noise floor is less than 2 $\mu\Omega$ for frequencies up to 100 MHz. The d.c. resistance of the instrument calibration sample was 14.5 $\mu\Omega$. The low frequency surface transfer impedance was 20.4 $\mu\Omega$, which compares favorably with the d.c. resistance. The low frequency surface transfer impedance matched the d.c. resistance much more closely when these values were in the range of the test samples (about 100 $\mu\Omega$), since the signal-to-noise ratio was much higher. Measurements made with the quadraxial test fixture and computer controlled network analyzers are expected to be accurate within 10 to 20 percent (1 to 2 dB).

TRANSFER IMPEDANCE OF BACKSHELL/BRAID TERMINATIONS

Backshell/Braid Termination Samples [2,3]

Figures 3 and 4 show the backshell termination terminations that were tested. The five samples shown in Figure 3 use variations of a pair of cones to terminate the braid to the backshell. The two samples shown in Figure 4 used techniques such as a large thread ("lightbulb") or circular coil spring to make the braid termination. Each sample, except the instrument calibration sample, had a 1-inch long piece of tinned copper braid between the RFI backshell termination and a 10 inch length of 1.0-inch diameter copper pipe that served as one of the mechanical attachment interfaces between the sample and the quadraxial test fixture. The RFI/EMI backshell end of the sample had an outer diameter of 1.0 inch, was 2.0 inches long and was constructed of nickel-plated aluminum. It had a 3.5-inch diameter flange which served as the attachment interface between the sample and the quadraxial test fixture. The sense wire was attached to the copper pipe as close to the connector/backshell interface as was practical. A termination resistor was not used on the sense wire for the backshell/braid termination measurements

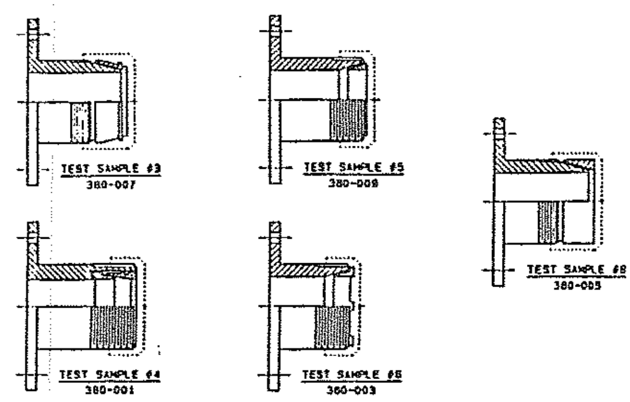

Figure 3. RFI/EMI Backshell Termination Test Samples that Used Dual Cones for Attaching the Shield Braid.

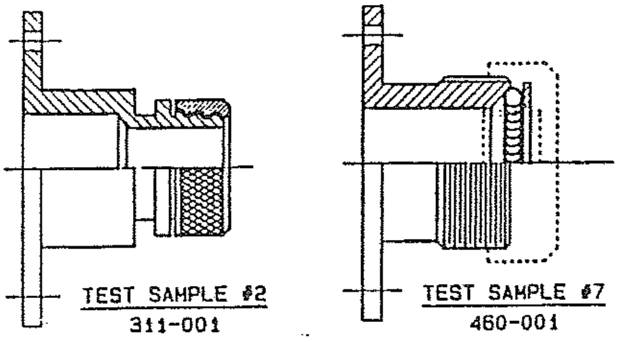

Figure 4. RFI/EMI Backshell Termination Test Samples that Used Large Screw Threads or a Circular Coil Spring for Attaching the Shield Braid.

in order to improve the sensitivity. This did not cause transit time resonances below 100 MHz because the entire fixture was electrically small in this frequency range.

An additional type of backshell/braid termination was measured in conjunction with another program. This backshell used a stainless steel band to attach the braid to the backshell. The test sample consisted of a empty MIL-C-81511 connector shell (shell size 18) attached to the 8.9-cm diameter adapter plate using 4 screws and solder, the backshell and 2.5-cm of braid which in turn was attached to the 15.9-mm copper pipe.

Results of Backshell/Braid Termination Transfer Impedance Measurements

Figure 2 showed the measured surface transfer impedance of the instrument calibration sample (a solid pipe), a reference sample (1 inch of braid soldered to the solid portion of the sample) and a sample in which 1 inch of braid was soldered to the copper pipe and swaged to the nickel-plated aluminum flange section of the sample. These data show that the reference sample had a transfer resistance of a little less than 0.1 mΩ and a transfer inductance (high-frequency transfer impedance divided by the angular frequency (2πf)) of about 10 pH. A typical (not worst case) braid, 1 inch in diameter, has a transfer resistance of about 4 mΩ/m and a transfer mutual inductance of between 400 and 800 pH [5]. Thus I inch of single braid (1/40 meter) would be expected to have a transfer impedance that is very close to the present measurements. There is little difference between the swaged braid sample and the reference (soldered) sample.

Figure 5 shows the measured transfer impedance of the reference sample (soldered braid), the swaged braid sample and a typical RFI/EMI backshell (sample 3) that used clamping cones. There was not significant difference between these three samples.

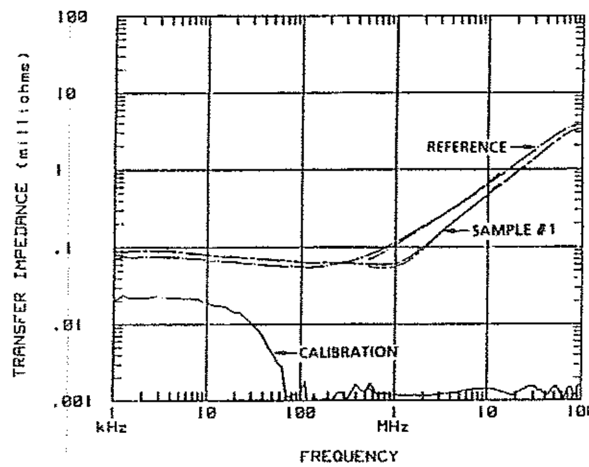

Figure 5. Measured Surface Transfer Impedance of the Reference Sample, the Swaged Braid Sample (#1), and a Typical Dual Cone RFI/EMI Backshell Termination (#3).

Figure 6 shows the measured transfer impedance of the five samples that used different variations of a pair of matching cones to attach the braid to the backshell as well as the reference sample. The measured transfer resistance of all these samples was about 0.1 mΩ and the transfer mutual inductance of most of the samples was about 10 pH. The exception was sample 6, which had a significantly higher surface transfer impedance above 500 kHz

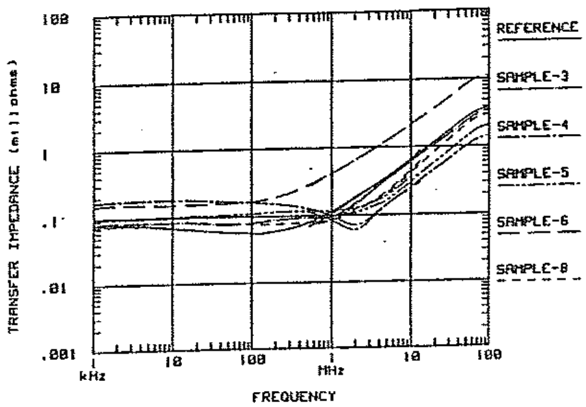

Figure 6. Surface Transfer Impedance Measurements of Five Dual Cone RFI/EMI Backshell Terminations.

than the rest of the samples. The design of this sample did not appear to be significantly different than the rest of the samples included in Figure 6; therefore it was thought that there may be a difference in the method whereby the braid was installed in the backshell. In order to test this hypothesis, the samples were taken apart, reassembled and remeasured. The results were comparable, except that three other samples had significantly higher transfer impedances at high frequencies rather than sample 6.

In order to find the reason for the change in the high frequency transfer impedance, various adjustments were made in the test fixture while observing the voltage response on the network analyzer display. The only thing that changed the high-frequency transfer impedance was a movement of the copper pipe which was soldered to the braid. Movement of this pipe changes the tension on the braid and therefore the size of the apertures and the contact impedance between the carriers in the braid. Previous measurements on braided cables have shown that there are two mechanisms for coupling electromagnetic energy through a braided shield. These are aperture coupling, which depends on the size of hole between the carriers, and porpoising coupling, which depends on the contact impedance between the carriers. These two contributions are opposite In phase. Therefore, they can cancel each other. Figure 7 shows the measured transfer impedance for three different amounts of tension on the braid--the initial or normal tension, the worst case and the best case. The worst case could be achieved by two conditions--pulling very hard or relaxing the braid as much as possible. The "best" position/tension was very sensitive to slight changes in the braid configuration.

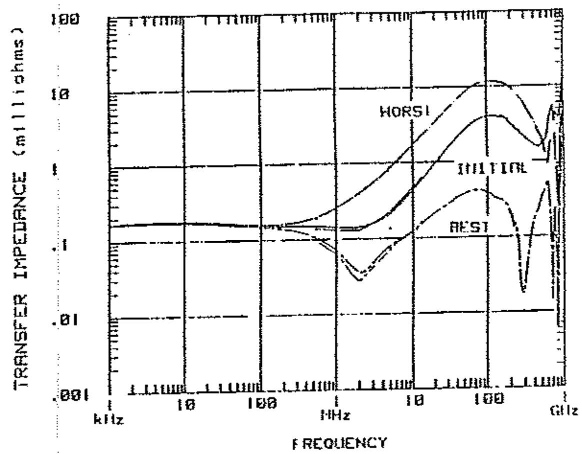

Figure 7. Several Measurements of the Surface Transfer Impedance of Sample 4, a Dual Cone RFI/EMI Backshell Termination, After Braid Tension Was Changed.

The measurements presented in Figures 5, 6 and 7 show that for the dual cone braid attachment backshell, the high frequency surface transfer impedance of the first inch of braid was much more significant than that of the braid-to-backshell attachment. Therefore, a cable designer could use other criteria such as integrity under vibration and thermal cycling, ease of manufacture, or ease of reassembly to choose between the various RFI/EMI backshell termination designs.

Figure 8 shows the measured surface transfer impedance of the sample that used a large screw thread (light bulb) to attach the shield braid. Three measurements were made of this sample as part of the initial test

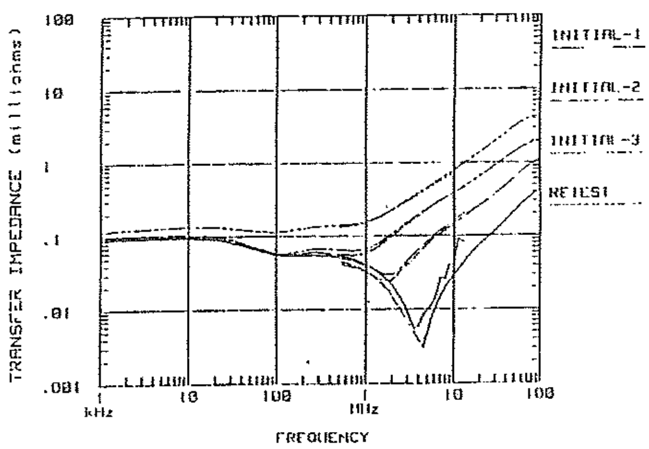

Figure 8. Measured Surface Transfer Impedance of an RFI/EMI Backshell Termination (Sample 2) that Used a Large Screw Thread to Attach the Shield Braid.

program. The transfer resistance did not change during this measurement sequence. The high frequency transfer impedance or mutual inductance, however, changed significantly. These changes are particularly evident between 1 and 10 MHz. After disassembly/reassembly, both the resistive and inductive components of the surface transfer impedance increased. To some extent this increase may be due to a change in torque during assembly. This sample was the only sample that required the assistance of a tool for disassembly. All the others were disassembled using only bare hands.

When it was reassembled, only bare hands were used. The changes in the high frequency surface transfer impedance are due to changes in the optimization of the short length of braid that is part of these samples as discussed in the preceding paragraphs.

Figure 9 presents the initial and final surface transfer impedance measurements for the sample that used a circular coil spring between cones to apply pressure between the braid and the backshell. The transfer resistance is significantly higher for this sample compared to the others and the transfer resistance changed significantly as a result of the disassembly/reassembly. This probably results from not using enough torque during assembly. Since making these measurements, one of the manufacturers of this type of backshell has recommended the use of 100 in-lbs of torque in order to ensure proper electrical performance.

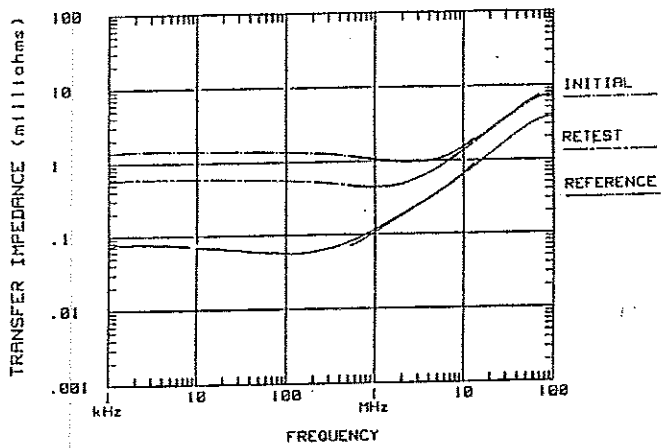

Figure 9. Measured Surface Transfer Impedance of an RFI/EMI Backshell Termination (Sample 7) that Used a Circular Coil Spring to Attach the Shield Braid.

SAMPLE NAME OR NUMBER	INITIAL MEASUREMENT		AFTER DISASSEMBLY/REASSEMBLY	
	D.C. RESISTANCE (MICROOHMS)	LOW FREQUENCY TRANSFER IMPEDANCE (MICROOHMS)	D.C. RESISTANCE (MICROOHMS)	LOW FREQUENCY TRANSFER IMPEDANCE (MICROOHMS)
INSTRUMENT CALIBRATION SAMPLE	14.3	20.4	------	------
BASELINE REF	71	72	------	------
SAMPLE-1	87	87.4	------	------
SAMPLE-2	76	88	116	116
SAMPLE-3	83	80	81.5	78
SAMPLE-4	181	171	154	152
SAMPLE-5	102	95	100	96
SAMPLE-6	134	148	121	117
SAMPLE-7	1320	1340	601	590
SAMPLE-8	87	81	97	96

Table 1. Comparative Data Before and After Disassembly/Reassembly

The d.c. resistance of each of the RFI/EMI backshell terminations was measured by passing 5, 10, and 20 amperes through the sample and measuring the voltage across the sample with a high impedance digital voltmeter. The three measurements on each sample were averaged to minimize measurement error. The data for the two series of measurements (original and after disassembly/reassembly) are tabulated in Table 1 and compared to corresponding low frequency transfer impedances.

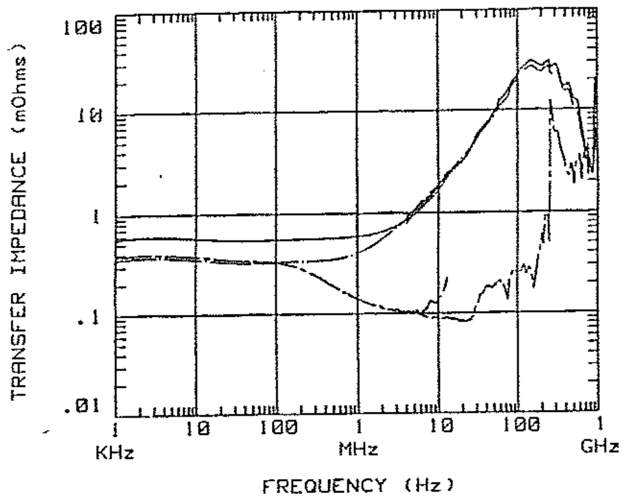

Figure 10. Measured Transfer Impedance of a Connector/Backshell that used a Metal Banded Braid Termination.

Figure 10 shows the measured transfer impedance of the connector/backshell/braid termination sample that used a metal band to attach the braid to the backshell. The upper-most plot is the transfer impedance when the connector/backshell was assembled with 100 in-lbs of torque. Next, maximum assembly torque was applied. The resulting transfer impedance measurement is shown in the middle plot. Finally, copper tape was placed over the braided portion of the sample and extended to the top of the metal band. The resulting transfer impedance measurement is shown in the bottom plot. These measurements can be explained as follows: The normal torque sample shows the typical resistance/mutual inductance characteristic of a braid termination. When the torque was increased, the resistance decreased indicating the resistance of the connector/backshell joint determines the electromagnetic shielding performance of typical connector/backshell samples below a few MHz. When copper tape was placed over the braid, aperture/porpoising coupling is this portion of the sample was greatly reduced and the transfer impedance of the complete sample decreased dramatically. Above 10 MHz, the measurement was at the noise level of the instrumentation used for these measurements.

In a quantitative sense, resistance and surface transfer impedance measurements of banded backshell showed that this termination could be characterized as a transfer resistance of about 100 μΩ. Aperture coupling, as evidenced by a mutual inductance, was not apparent. Electromagnetic coupling through the banded braid to backshell joint was not significant for frequencies between 10 MHz and 11 GHz. These measurements also showed that the transfer resistance of the interface between an olive drab over cadmium-plated connector and a bright nickel-plated backshell was about 300 μΩ for an assembly torque of 100 in-lbs. The backshell barrel had an average resistance of 6.75 μΩ. Thus, the low frequency measurements were dominated by the resistance of the connector/backshell interface and the high frequency measurements were dominated by the mutual inductance of the inch of single braid that was part of each sample.

METALLIC CIRCULAR CONNECTORS

The transfer impedance of a metallic circular connector is dominated by the three interfaces (braid termination, connector backshell and plug receptacle) since the resistance of the shell or barrel portions is insignificant. The transfer impedance of braid termination techniques has already been discussed. The transfer impedance of the connector/backshell and plug receptacle interfaces was determined by measuring specially constructed samples that included only the connector/backshell interface and comparing it to transfer impedance measurements of a complete metallic connector/backshell/braid assembly.

Transfer Impedance of the Connector/Backshell Interface [4]

Test Samples

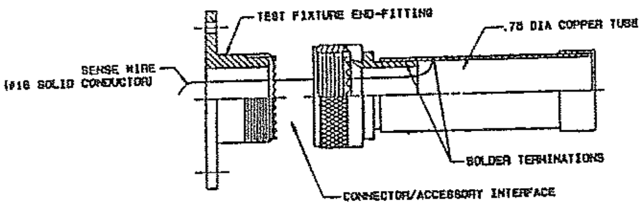

Figure 11. Side View of a Typical Interface Sample.

Figure 11 shows a side view of a typical connector/backshell interface sample. Figures 12 and 13 show details of the eight connector/backshell interfaces that were tested. The backshell side of the interface was soldered to a 0.254-m (10-inch) length of 0.019-m (.75-inch) diameter solid copper pipe that served as one of the mechanical attachment interfaces between the sample and the quadraxial test fixture. The connector end of the sample had an outer diameter of 0.0254-m (1 inch), was 0.0508-m (2 inches) long, and was constructed of nickel plated aluminum. It had a 0.089-m (3.5-inch) diameter flange that served as the attachment interface between the sample and the test fixture. The connector/backshell samples were assembled with a torque of greater than 100 in-lbs.

Results of Connector/Backshell Measurements

Figure 14 shows the measured transfer impedance of the instrument calibration sample (a solid pipe) and two variations of the MS 3155 connector/backshell interface. One of these samples had three clocking teeth and one had a full set of such teeth. Two measurements from the three-tooth sample are shown in Figure 14. In the initial measurement, the surface transfer impedance was proportional to frequency above 1 MHz. This frequency dependence was indicative of aperture coupling. Examination of the test sample revealed that the teeth on the "connector" were wider than the mating teeth on the "backshell." This mechanical mismatch resulted in a gap between the two parts of the sample. After the "connector" teeth were machined so that they fit in the "backshell," the surface transfer impedance was reduced by over an order of magnitude. Between 10 and 100 MHz, the

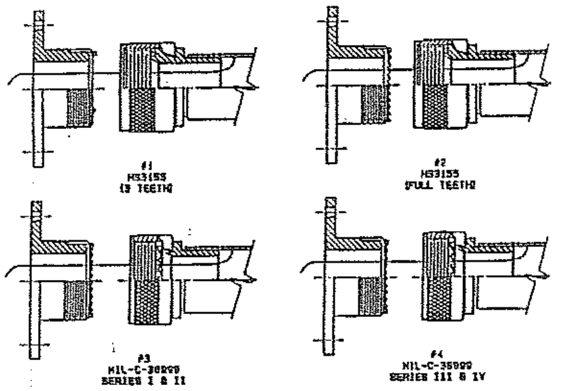

Figure 12. Details of the MS 3155 and MIL-C-38999 Interfaces

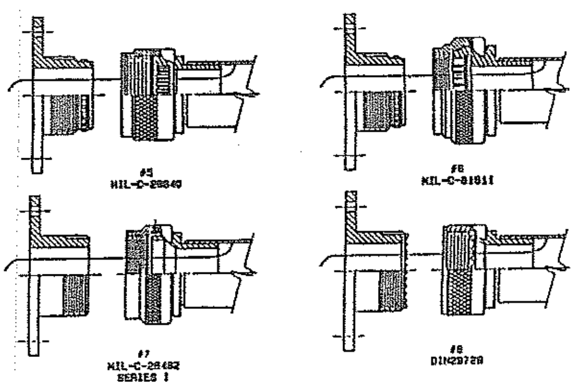

Figure 13. Details of the MIL-C-28840, MIL-C-81511, MIL-C-26482, and DIN 29729 Interfaces.

transfer impedance of the modified sample still increased but was proportional to the square root of frequency. This suggests that the coupling mechanism is contact impedance rather than aperture coupling. The surface transfer impedance of the MS 3155 sample with a complete set of clocking teeth decreased with frequency up to about a megahertz. Above a megahertz, the transfer impedance was below the noise level of the system. These measurements suggest that the sample with full teeth was almost as good as a solid cylindrical shield.

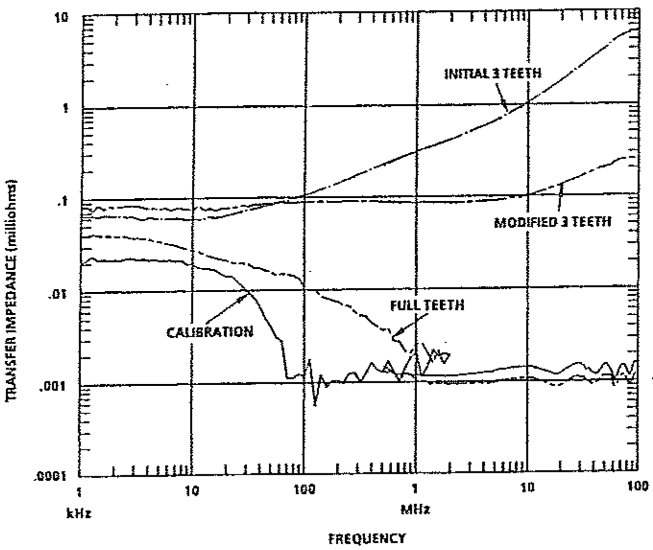

Figure 14. Surface Transfer Impedance of Samples Using the MS 3155 Connector/ Backshell Interface.

Figure 15 shows the measured surface transfer impedance of two samples that used clocking teeth that were located on the side of the sample. These samples were constructed according to MIL-C-28840 and MIL-C-81511. The surface transfer impedance of both samples was similar. It decreased with frequency but was significantly higher than that of the calibration sample. Since the surface transfer impedance decreased with frequency, pure aperture coupling could not be taking place. A much more likely mechanism was contact impedance coupling internal to the connector/backshell sample.

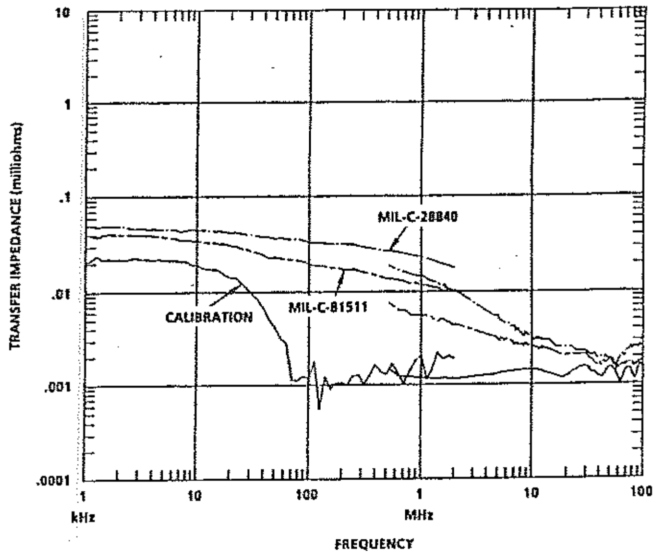

Figure 15. Surface Transfer Impedance of Samples Using the MIL-C-81511 and MIL-C-28840 Connector/Backshell Interfaces.

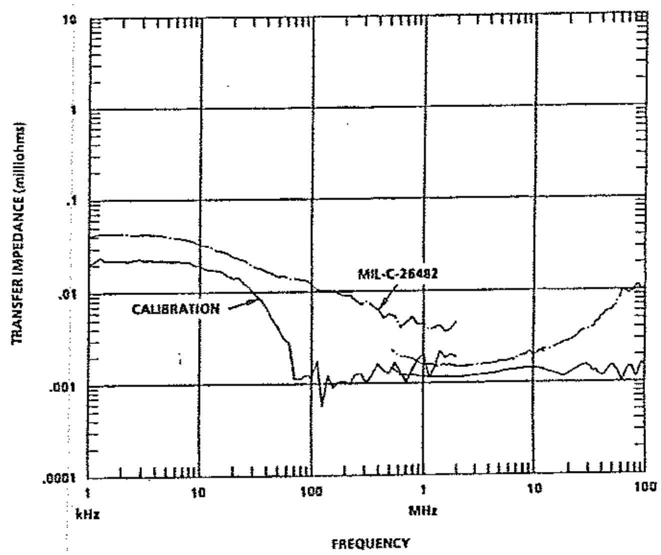

Figure 16. Surface Transfer Impedance of the MIL-C-26482 Connector/Backshell I nterface.

Figure 16 shows the measured transfer impedance of the sample that incorporated the MIL-C-26482, Series I interface. Up to about 5 MHz, the surface transfer impedance of this sample decreased with frequency and was almost as good as the calibration sample. Above 10 MHz, the transfer impedance of this sample increased with frequency and was almost proportional to frequency. This suggests that its electromagnetic performance was being limited by aperture coupling. The effective mutual inductance of this sample was about 0.02 pH, which is extremely small. The construction of this connector/backshell interface did not incorporate any teeth at the interface.

Figure 17 shows the measured surface transfer impedance of a sample that incorporated the DIN 29729 interface. The transfer impedance of this sample was almost as good as that of the solid calibration sample.

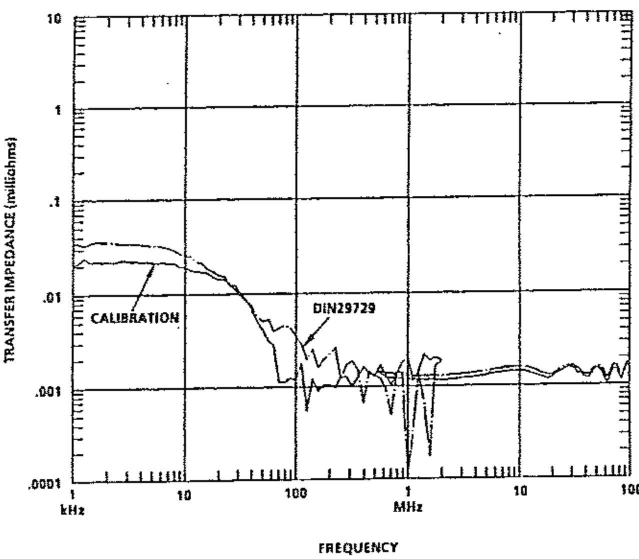

Figure 17. Surface Transfer Impedance of the DIN 29729 Connector/Backshell Interface.

Figure 18 shows the measured transfer impedance of samples that used the two kinds of connector/backshell interfaces specified for the MIL-C-38999 connector. The instrument calibration sample was again included for reference. The surface transfer impedance of the sample using the Series

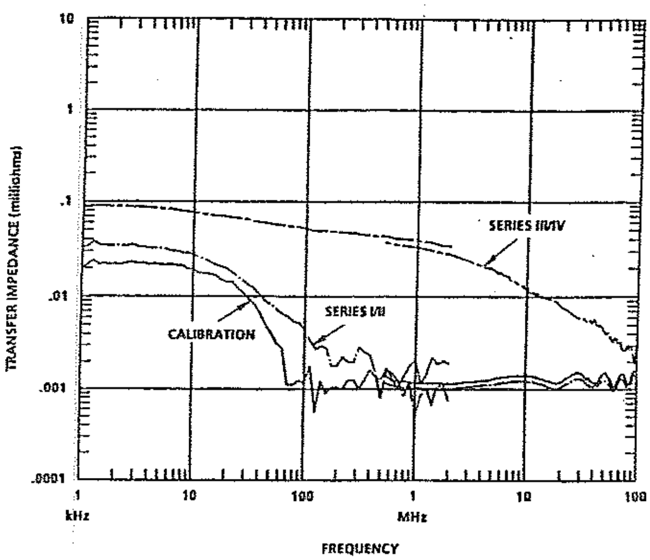

Figure 18. Surface Transfer Impedance of Samples Using the MIL-C-38999 Connector/ Backshell Interface.

I/II interface was not significantly different from the transfer impedance of the calibration sample. This suggests that the transfer impedance of the connector/backshell interface was small compared to that of either sample. The measured surface transfer impedance of the sample using the Series III/IV interface decreased with frequency, but was significantly higher than the transfer impedance of the sample with the Series I/II interface. The electromagnetic performance of both would be considered good by most standards. However, since the only difference in these samples is the type of threads used to attach the backshell to the connector, these data suggest that sample-to-sample variation may be more significant than the electromagnetic performance of a particular sample, or that the relatively poor performance of the sample that used the Series III/IV interface was due to an improper assembly torque.

In order to explore the latter hypothesis, a second set of measurements was performed. The sample was disassembled, the disassembly torque was measured, and the surface transfer impedance was measured after the connector/backshell was assembled with specified torque. The disassembly torque was about 250 in-lbs. During reassembly, it was noticed that the connector/backshell screw threads had a certain roughness. After making preliminary electromagnetic measurements which were somewhat inconsistent, the threads were lubricated with light oil and the measurements were repeated. The results are shown in Figure 19 At 25 in-lbs, the transfer impedance was almost frequency independent. As the torque was increased, the surface transfer impedance decreased. This was particularly evident at the high frequencies. At 200 in-lbs, the transfer impedance of the sample that used the MIL-C-38999, Series III/IV interface approached that of the sample that used the Series I/II interface. Thus, the initial measurement of the sample that used a MIL-C-38999, Series III/IV interface was anomalously high because a lack of lubrication prevented the assembly from coming together properly.

Feature-wise, the DIN 29729 interface was similar to the MIL-C-38999 interface. The measurements performed in this study showed that the electromagnetic performance of samples that incorporated these interface features was similar.

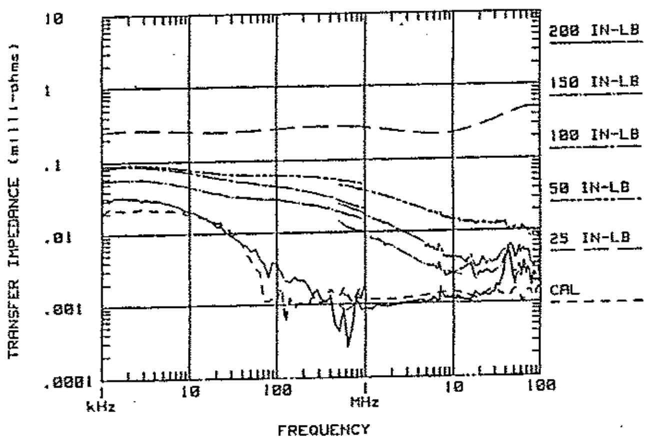

Figure 19. Effect of Torque on the Surface Transfer Impedance of a Sample using the MIL-STD-38999, Series III/IV Connector/Backshell Interface.

Discussion of Connector/Backshell Transfer Impedance Measurements

With the exception of the measurements made on the sample that used only three clocking teeth, all of the connector/backshell interface samples had extremely small or unmeasurable mutual inductances. Thus, for frequencies up to 100 MHz, aperture coupling was not a significant coupling mechanism for common connector/backshell interfaces. This statement may also be true above 100 MHz, but cannot be supported by the presently available data. In three of the samples, the measured surface transfer impedance was very close to that of a solid copper calibration pipe. In four of the samples, the measured transfer impedance decreased with frequency but was not as good as a solid calibration sample. Typical transfer resistances were in the 30- to 90-$\mu\Omega$ range. In only one sample was aperture coupling the dominant coupling mechanism, but its effective mutual inductance was very low (about 0.02 pH). The data suggests that contact impedance coupling was evident in many of the samples.

The surface transfer impedance measurements performed on the sample that incorporated the MIL-C-38999, Series III/IV interface showed that torques in the range of several hundred in-lbs are necessary in order for the connector/backshell interface to have insignificant contact impedance. In addition, lubrication was necessary in order to achieve smooth assembly and consistent electromagnetic measurements

The surface transfer impedance measurements of a variety of backshell/braid termination interfaces shows that they typically have a surface transfer resistance of about 0.1 mΩ and a transfer mutual inductance of about 10 pH. These measurements showed that the short 1-inch length of single overbraid incorporated in the samples was more significant than most variations in the design of the backshell/braid termination. Comparison of the surface transfer impedance of the connector/backshell interface with the surface transfer impedance of the backshell/braid termination shows that there was less electromagnetic coupling through the connector/backshell interface for frequencies below 100 MHz than there was through the backshell/braid termination. The surface transfer resistance of the connector/backshell interface was roughly half that of typical backshell/braid terminations. The transfer mutual inductance of the worst sample measured in the present study except for the MS 3155 sample with only three teeth) was roughly 500 times (54 dB) smaller than the transfer mutual inductance of the inch of single overbraid that was part of the braid termination samples. Even the MS 3155 connector/backshell interface sample with only three teeth had a surface transfer impedance that was more than an order of magnitude (20 dB) less than that of the inch of single overbraid.

Transfer Impedance of a Complete Circular Connector/Backshell/Braid Termination

Figure 20 shows the surface transfer impedance of a typical high quality complete connector/backshell/braid termination (MIL-C-38999, Series IV) [6]. The surface transfer resistance of the complete assembly was roughly three or four times that of the backshell/braid termination. The high frequency response (10 to 100 MHz) of the complete assembly was about the same as that of the backshell/braid termination assembly; however, it had a different frequency dependence. The surface transfer impedance of the complete assembly was proportional to the square root of frequency for frequencies above 10 MHz, while the transfer impedance of the backshell/braid termination was proportional to the first power of the frequency. The square root frequency dependence suggests contact impedance coupling at the spring fingers located between the connector plug and its receptacle, whereas the first power of frequency dependence was due to either aperture or porpoising coupling through the overbraid. Therefore, the contributions of the 1 inch of single overbraid and the contact impedance of the spring fingers were comparable. Either may dominate in a particular assembly. In any case, apertures within the connector/backshell are not a dominant coupling mechanism. This is consistent with theory that predicts that the contribution of the apertures between the spring fingers is negligible for frequencies below several hundred megahertz because of the below cutoff attenuation of the waveguide formed by the plug and receptacle barrels.

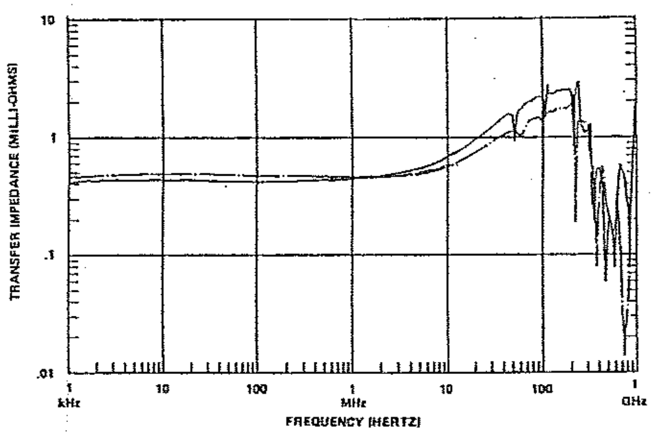

Figure 20. Two Measurements of the Same MIL-C-38999-500, Series IV Connector Before and After Mating.

TRANSFER IMPEDANCE OF COMPOSITE CIRCULAR CONNECTORS

In recent years, several so-called "composite" connector/backshell/braid termination assemblies have become available. These assemblies have rugged plastic barrels or shells which have been plated with various combinations of metal. Their virtue is that they are very corrosion resistant since they do not contain the aluminum used as the base metal of most connectors. The metal plating on metallic connectors generally does not protect the connector against corrosion since it usually contains cracks and scratches. These connector/backshell assemblies generally have a transfer resistance of 7 to 15 mΩ and a transfer mutual inductance determined by the backshell/braid termination interface. They can be built to meet all the shielding requirements of metallic connectors since these requirements start at 100 MHz. Note that these connectors cannot carry as much current as metallic connectors and some use a ferro-magnetic nickel plating that could saturate at high current levels. Having stated these caveats, the composite connector/backshell assembly has great potential for providing good electromagnetic shielding throughout the life of the system on which it is installed.

TRANSFER IMPEDANCE OF RECTANGULAR CONNECTORS

Circular connectors can provide excellent electromagnetic shielding because they have no deliberate apertures and they are generally assembled by means of threaded interfaces. Rectangular connectors, such as the DB-25 subminiature connectors used on computers and the MIL-C-83733C rack-and-panel connectors, on the other hand are more difficult to shield because their interfaces are more subject to aperture coupling. Originally, there were no electromagnetic compatibility shielding requirements on such connectors. Now, with electromagnetic compatibility requirements becoming more stringent (particularly for digitally controlled equipment), these connectors must be part of an electromagnetically shielded interconnect or cable system. Transfer impedance measurements are available on two types of rectangular connectors--the DB-25 subminiature and the rack-and-panel connectors.

DB-25 Subminiature Connectors [7]

Test Samples

Nine DB-25 subminiature connector/backshell samples as well as two reference samples were measured under this program. Two types of connector pairs were used in constructing the samples. Two samples used plugs that incorporated dimples in the shell or "barrel" to facilitate better contact between the plug and receptacle. The rest of the plugs did not have such dimples. All the samples had stamped metal cases with appropriate plating. Except for the sample that used the pigtail braid termination, all of the pins of the sample were connected together. A short length of shielded cable was attached to the pins of the connector plug. About 2.5 cm of this cable was unshielded, and about 2.5 to 3 cm of the cable was shielded with double braid. The braid was soldered to a 15.9 mm outer diameter copper pipe which allowed the sample to be attached to the test fixture. The center conductor of the shielded cable served as the sense wire and was soldered to the copper pipe.

The connector receptacle was attached to a circular brass adapter plate, 8.9-cm in diameter. All pins were connected together, except in the case of the sample that used the pigtail braid termination. The brass adapter plate allowed the connector/backshell sample to be attached to the quadraxial test fixture.

The test samples differed in the type of backshell used, whether or not the plug used a dimpled "barrel," and whether or not a gasket was used under the connector receptacle.

The most robust backshells consisted of a two piece nickel plated die-cast backshell that used several methods for circumferentially clamping and therefor terminating the cable braid. These included a pair of cones and a compression insert. The dual cone braid termination clamped the cable braid between two metal cones, while the compression insert termination compressed the cable braid between the two halves of the backshell after it was drawn back over a rubber grommet. Transfer impedance measurements of the dual cones described earlier had shown that it was less than the transfer impedance of 2.5 cm of single braid. The dual cone backshell was measured with and without a gasket under the connector receptacle. The gasket was recommended by the backshell manufacturer and consisted of a metal mesh filled with plastic. The compression insert connector/backshell assemblies was measured with and without a dimpled plug.

Four of the samples used metallized plastic backshells. One of these samples used a set screw to mechanically secure the backshell to the braid and to provide an electrical connection between these parts. The other sample used a strain relief clamp on the cable braid. This device fit into a cavity of the backshell and provided both a mechanical and electrical termination of the braid. Two of the samples, one with a dimpled plug and one without, consisted of metallized plastic backshells with a compression insert braid termination similar to that used for two of the die-cast backshell samples.

The final sample used a dielectric (non-conductive) backshell which provided a mechanical termination for the cable. A short length (2.5 cm) of AWG #22 wire provided an electrical termination between the cable braid and pin 1 of the connector pair. Pin 1 of the receptacle was connected to the connector shell by means of a short length of wire. This sample was referred to as the pigtail braid termination sample.

The two reference samples consisted of a sample that incorporated 2.5 cm of double braid from the shielded cable and a copper pipe with a 4 mm hole. Both of the reference samples had an 8.9 cm diameter adapter plate at one end and a 15.9 mm diameter copper pipe at the other end. The measured transfer impedance of the braid sample was consistent with that of other double braided samples [5]. The measured transfer impedance of the solid pipe samples showed that below 100 kHz, the noise floor was 20 to 40 dB below the levels expected from the connector/backshell samples.

Results of DB-25 Subminiature Connector Transfer Impedance Measurements

Figure 21 shows the measured transfer impedance of the connector backshell combination that used a two piece die-cast backshell and a braid termination which clamped the braid between two metal cones. Measurements are shown of this combination with and without a plastic filled metal mesh gasket under the connector receptacle. The measurements without the gasket installed under the receptacle were among the lowest of this test series. This combination had a transfer resistance of less than a mΩ and a transfer mutual inductance of about 50 pH. Between 300 kHz and 30 MHz, the transfer impedance increased as the square root of frequency, suggesting that the two attaching screws provided the principle path between the plug and the receptacle. The square root dependence is expected when contact is made at a few discreet points. Because of the skin depth effect, the current does not diffuse completely into the conductor. Therefore, the resistance will increase with frequency. Because of the inverse square root frequency dependence of the skin depth, the resistance is proportional to the square root of frequency. When a gasket was placed under the receptacle, the transfer resistance increased to 2 mΩ. In fact, for all frequencies below 100 MHz the gasketed connector provided poorer electromagnetic performance. This is undoubtably due to the relatively poor conductivity of the gasket material.

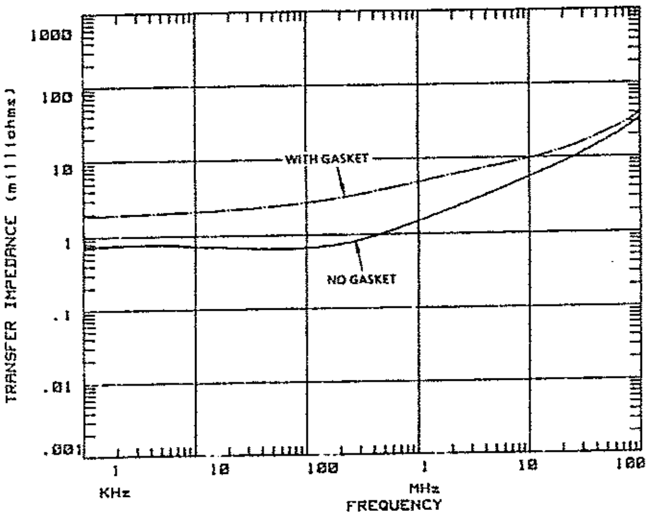

Figure 21. Surface Transfer Impedance of DB-25 Subminiature Connector/Backshell Combinations that used a Die-Cast Backshell and a Dual Cone Braid Termination.

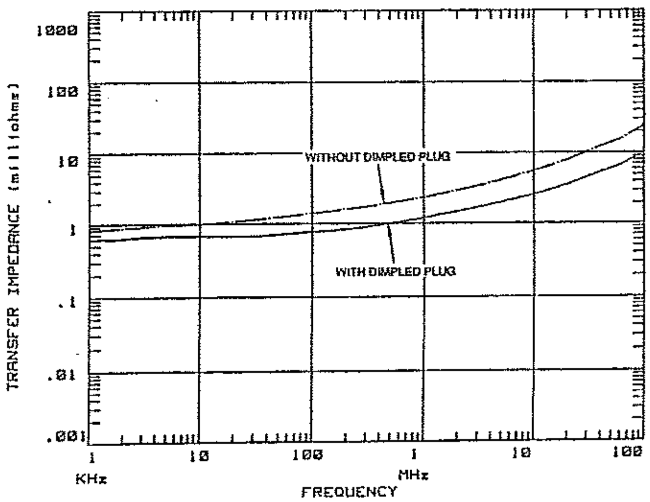

Figure 22. Surface Transfer Impedance of DB-25 Subminiature Connector/Backshell Combinations (with and without Dimpled Plug) that used a Die-Cast Backshell and a Compression Insert Braid Termination.

Figure 22 shows the measured surface transfer impedance of two connector backshell combinations that used metal die-cast backshells with a compression insert braid termination, with and without a dimpled plug. Comparison of the ungasketed dual cone termination of Figure 21 with the undimpled plug of Figure 22 shows that the compression insert braid termination was about as good as the dual cone braid termination. The transfer impedance of the dual cone braid termination was slightly better than the compression insert braid termination in the 10 kHz to 10 MHz frequency range. The compression insert braid termination also displayed the square root of frequency dependence at the higher frequencies suggesting that the two attachment screws or other small parts of the connector are the principal connections between the plug and the receptacle.

When a dimpled plug was used the electromagnetic shielding performance improved significantly. The transfer resistance decreased slightly from 0.83 to 0.6 mΩ. While the high frequency response of the dimpled connector was still proportional to the square root of frequency, it was almost a factor of 3 (10 dB) better than the undimpled plug. This was consistent with the improvement in the shielding effectiveness (as measured with an absorbing clamp) previously reported for such connectors [8].

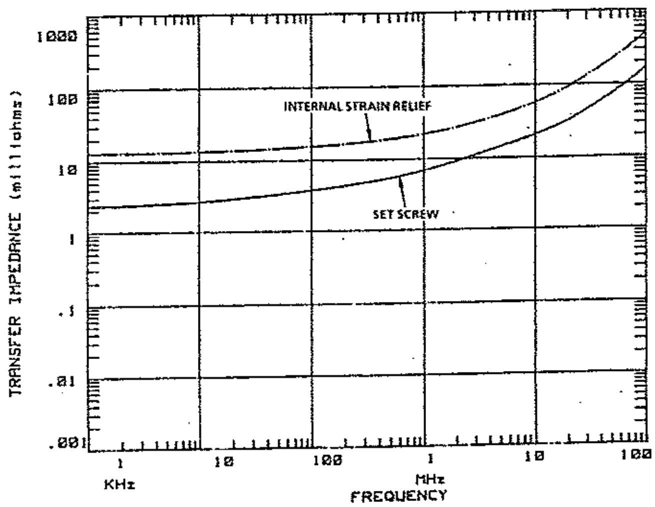

Figure 23. Surface Transfer Impedance of DB-25 Subminiature Connector/Backshell Combinations that used Metallized Plastic Backshells.

Figure 23 shows the measured surface transfer impedance of two connector/backshell combinations that used metallized plastic backshells. The metallized plastic backshell with a set screw braid termination had a transfer resistance of about 2.5 mΩ and a transfer mutual inductance of almost 250 pH. Like the previous sample, only at the highest frequencies was the surface transfer impedance proportional to frequency. Between 1 kHz and 50 MHz, the transfer impedance slowly increased, suggesting that the contact impedance between the parts of the connector/backshell was an important coupling path.

The sample that used a metallized plastic backshell with an internal strain relief clamp to make contact between the braid and the backshell was significantly worse than the sample that used a set screw. Its transfer impedance was almost an order of magnitude higher. This was undoubtably due to the much poorer contact provided by this braid termination method.

Note that the electromagnetic performance of both of the braid termination methods used by the samples shown in Figure 23 would be expected to degrade with time, since the plastic wire insulation will slowly flow, thus relieving the pressure in the braid termination.

Figure 24 shows the measured surface transfer impedance of the connector/backshell combination that used a metallized plastic backshell, with and without a dimpled plug. The transfer impedance of the metallized backshell with the compression insert braid termination (without a dimpled plug) was very similar to that shown in Figure 23 for the metallized plastic backshell with a set screw braid termination. The transfer resistance was determined by the conductivity of the backshell plating and the two attaching screws. The addition of dimples to the connector plug significantly improved the electromagnetic shielding performance, particularly at high frequencies. Between 1 and 100 MHz, the dimpled plug reduced the transfer impedance by almost an order of magnitude. In this frequency range, the metallized plastic backshell with dimpled plug was equivalent to the die-cast backshell with dimpled plug shown in Figure 22.

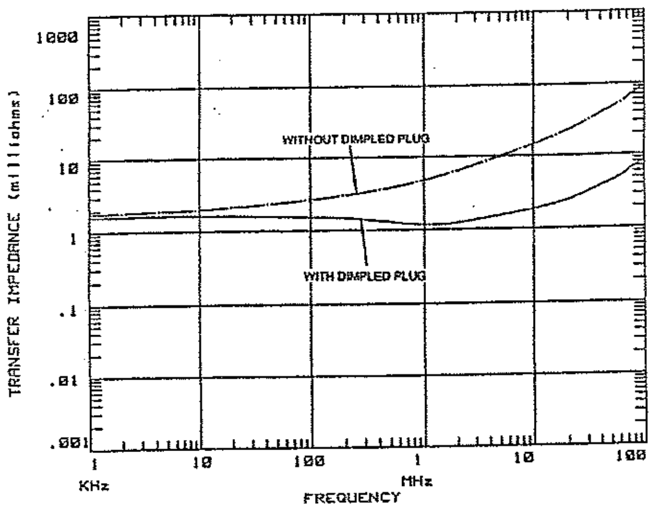

Figure 24. Surface Transfer Impedance of DB-25 Subminiature Connector/Backshell Combinations (with and without Dimpled Plug) that used a a Compression Insert Braid Termination.

Finally, the surface transfer impedance of a sample that used a dielectric backshell but provided a 2.5 cm long wire for connecting the braid to the connector shell is shown in Figure 25 This sample had the worst electromagnetic performance of those measured in this test series. It had a transfer resistance of slightly more than 10 mΩ and a transfer mutual inductance of about 80 nH. Above 30 kHz, the transfer impedance is proportional to frequency, indicating that it behaves like a mutual inductance. This inductance is almost all accounted for in the self inductance of the length of wire that connects the braid to the connector shell. The total length of the two wires and the pins is about 5 cm. If one assumes the self inductance of the wire is about 1 μH/m, the inductance of a 5 cm length of wire would be 50 nH, which is reasonably close to the measured inductance of connector/backshell.

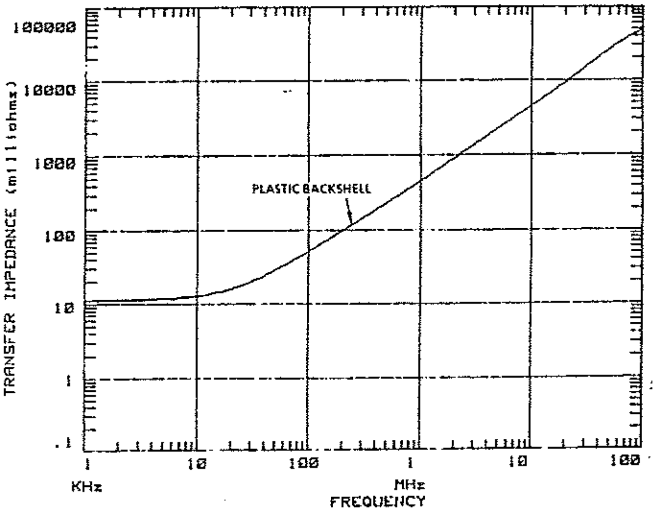

Figure 25. Surface Transfer Impedance of a DB-25 Subminiature Connector/Backshell Combination that used a Non-Conducting Backshell and a Pigtail Braid Termination.

Discussion of DB-25 Subminiature Connector Transfer Impedance Measurements

Good circular connector assemblies, such as those specified by MIL-C-38999, series 4, with quality backshells typically have a transfer resistance of about 0.5 mΩ and a transfer mutual inductance of less than 10 pH [6]. The mutual inductance of these connector assemblies is almost all accounted for in the mutual inductance of the 2.5 cm of braid that was part of the test samples. The transfer resistance of the DB-25 subminiature connector/backshell assembly, without a dimpled plug, was almost as good as that of a circular connector assembly. However, at high frequencies, its performance was about an order of magnitude worse than a good circular connector/backshell assembly. With a dimpled plug, the high frequency performance of the DB-25 subminiature connector was almost as good as a circular connector.

The measurements made as part of this test series show that the DB-25 subminiature connector can be made into a satisfactory shielded interconnect assembly if a quality backshell is used. Radiated emissions from a connector/backshell combination with a transfer resistance of less than a milliohm should not be serious for signals normally used to communicate to peripherals such as printers or modems that have maximum transfer rates of 9600 baud. For transfer rates in the MHz range, such as might be found on Small Computer Systems Interface (SCSI) lines, the shielding performance of even the best of the DB-25 connector/backshell combinations without dimples may be marginal. With dimples, the shielding performance would probably be adequate. From a susceptibility point of view, the best DB-25 connector/backshell (die-cast backshell with circumferential braid termination and dimpled plug) would probably be adequate for most situations. For example, a 10 A, 10 MHz damped sine wave transient would produce a voltage on the inside of the connector of about 10 mV if the transfer mutual inductance was 16 pH ($V = I\ 2\pi\ f\ M$). This would generally be insignificant compared to normal signals in the 1-5 V range.

A principle disadvantage to the DB-25 subminiature connector is that the electromagnetic shielding performance is primarily determined by the contact resistance between parts that are only loosely defined. This is particularly true of the combinations that used metallized plastic backshells. Because of the rather loose fit between the backshell and the connector, the surface transfer impedance will probably degrade with time due to oxidation, corrosion and dirt accumulation. These interfaces should probably also be adversely affected by vibration.

Rack and Panel Connectors [9]

Rack and Panel Test Samples

Three types of rack-and-panel connectors were investigated. The first test sample consisted of a standard rack-and-panel connector pair consisting of a receptacle mounted on a chassis and a plug, with backshell installed. Contact between the receptacle and plug is normally provided only by casual contact between its mating surfaces. Initial measurements of the standard rack-and-panel configuration (i.e., without spring fingers) showed erratic values for the plug to receptacle resistance. These varied from 2.8 milliohms to open circuit. It was obvious that a standard rack-and-panel connector would require some additional contact points between the plug and receptacle if it were to achieve acceptable transfer impedances, if only at low frequencies. Because of this inconsistent behavior of the standard rack-and-panel connector pair, additional grounding studs (1.25 cm long, 1 mm in diameter) were added to sides of the sample.

The second test sample consisted of an EMI shielded version of the rack-and-panel connector plug. This plug incorporated spring fingers around the perimeter of the mating surface. These contained no adhesive and remained on the connector by the clamping action of the spring fingers. The same standard receptacle was used with both plugs. Both samples were constructed of die-cast aluminum with nickel plating.

The same backshell used was used on both the standard and the EMI shielded version of the first rack-and-panel connector. It was constructed of die-cast aluminum and was a split shell design. This type of backshell is designed for EMI applications and normally included dual cones for circumferentially clamping and therefore terminating the cable braid. This braid termination method had been characterized previously [2], therefore the braid termination device was removed and replaced with a simple brass plate in order to simplify the test fixture. This backshell was also provided with two types of gaskets for the connector/backshell interface. One gasket consisted of wire screen impregnated with an elastomer while the other was a monel wire mesh. Measurements were performed with both types of gaskets.

A third test sample became available later in the program. Functionally, it was the same as the second sample and it had the same dimensions. Both the connector and the backshell were fabricated by a different manufacturer than the first and second sample. It too incorporated spring fingers around the perimeter of the plug/receptacle mating surface. The backshell was a solid die-cast design made of nickle plated aluminum. Two types of gaskets were available for the plug/backshell interface, one made of conductive particle filled elastomer and one made of sintered stainless steel fiber.

Test Methodology Used for Rack-and-Panel Connector Transfer Impedance Measurements

The surface transfer impedance of various rack-and-panel connector configurations was measured over the frequency range of 1 kHz to 100 MHz using a custom test fixture and a computer controlled HP3577A network analyzer. The test fixture is shown in Figure 26. It is essentially a triaxial test fixture. The connector receptacle was mounted to a test box using four bolts. A single pin was used to pass the sense wire through the receptacle to the plug or backshell. This allowed the surface transfer impedance of either the plug/receptacle or the plug/receptacle/backshell interfaces to be measured. The output of the network analyzer was connected to the backshell by

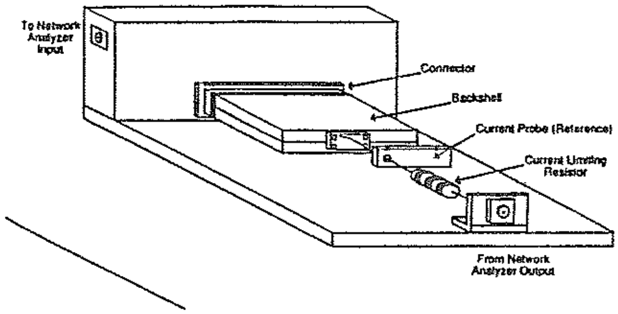

Figure 26. Test Fixture Used for Measuring Transfer Impedance of Rack-and-Panel Connectors.

means of a 50 Ω current limiting resister. The current then flowed across the backshell, over the backshell/plug, plug/receptacle and receptacle/chassis interfaces to the ground plane of the test fixture. The current was measured with a Tektronics CT-2 current probe. For all test configurations the receptacle remained bolted to the test box and was not altered. The measurement noise level of this measurement set-up was about 20 dB below the lowest transfer impedance measurement.

Results of Rack-and-Panel Transfer Impedance Measurements

Figure 27 shows the measured transfer impedance of the standard rack-and-panel connector with ground studs. Measurements with the sense wire terminated on the connector and on the backshell are both shown. At low frequencies, below several tens of kHz, the transfer resistance was a little less than 2 mΩ. This compared favorably with the d.c. resistance of this configuration. Above 40 kHz, the transfer impedance increases at almost 20 dB per decade. At 100 MHz, the transfer impedance was 1 Ω. This behavior is indicative of a mutual inductance caused by such features as apertures or finite length contacts.

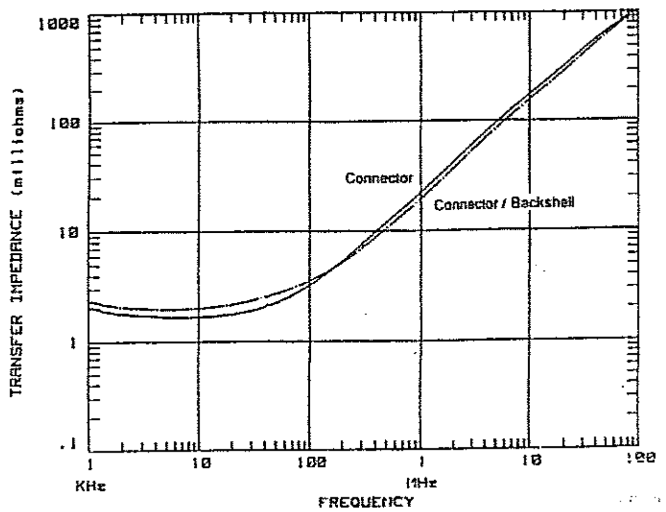

Figure 27. Surface Transfer Impedance of a Standard Rack-and-Panel Connector with Supplementary Ground Studs.

Figure 28 shows the measured surface transfer impedance for a EMI rack-and-panel connector which used spring fingers to reduce electromagnetic coupling at the plug/receptacle interface. Measurements were taken with sense wire terminated on the plug and on the backshell, thus allowing the transfer impedance of the receptacle/plug and the receptacle/plug/

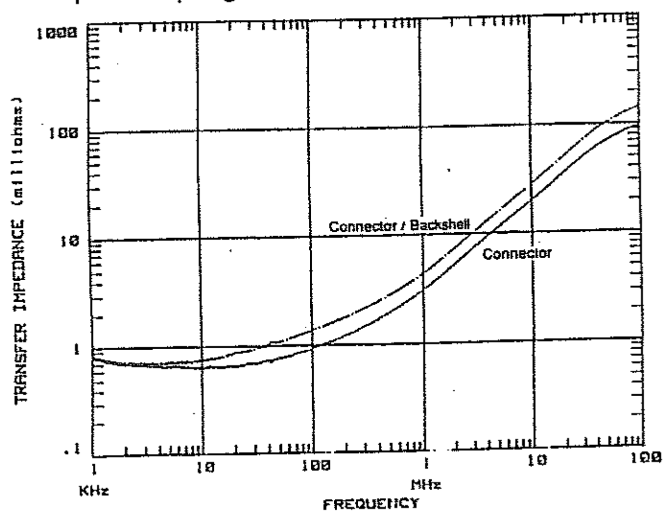

Figure 28. Surface Transfer Impedance of an EMI Rack-and-Panel Connector and Backshell without a Gasketted Plug/Backshell Interface.

backshell interface to be obtained. The plug/ backshell interface was not gasketted for these measurements. The spring fingers reduced the low frequency transfer impedance, the transfer resistance, by about a factor of two and reduced the high frequency transfer impedance by almost an order of magnitude (20 dB). The frequency dependence of the transfer impedance is somewhat less that 20 dB/decade suggesting that the coupling mechanism is a combination of aperture coupling and frequency dependent contact impedance. Notice that even when the sense wire was connected only to the plug, the transfer impedance was still quite high (100 mΩ at 100 MHz). As will be seen later, the ungasketed plug/backshell interface allowed electromagnetic energy into the back of the plug and induced a voltage on the sense wire.

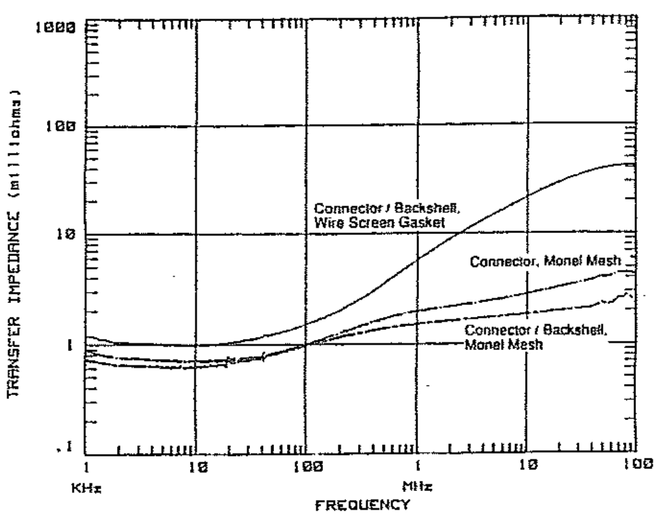

Figure 29. Surface Transfer Impedance of an EMI Rack-and-Panel Connector and Backshell with a Gasketted Plug/Backshell Interface.

Figure 29 shows the measured surface transfer impedance of EMI rack-and-panel connector/ backshell combination with two types of gaskets installed on the plug/backshell interface. For measurements using the monel mesh gasket, the sense wire was terminated at two locations (i.e., the connector and the backshell) allowing contributions of both the receptacle/plug and the plug/backshell interfaces to be determined. The elastomer impregnated wire screen decreased the transfer impedance at 100 MHz by a factor of 3 (10 dB) while the monel mesh gasket decreased the transfer impedance at 100 MHz to a few milliohms. The gaskets did not appreciably affect the transfer resistance (transfer impedance at low frequencies).

Figure 30 shows the surface transfer impedance of the second EMI rack-and-panel connector and backshell without a gasketted plug/backshell interface. While the shape of the measured transfer impedance curve is similar to that of the first sample (Figure 27), it is about a factor of 3 or 10 dB lower. There was no obvious reason for this difference.

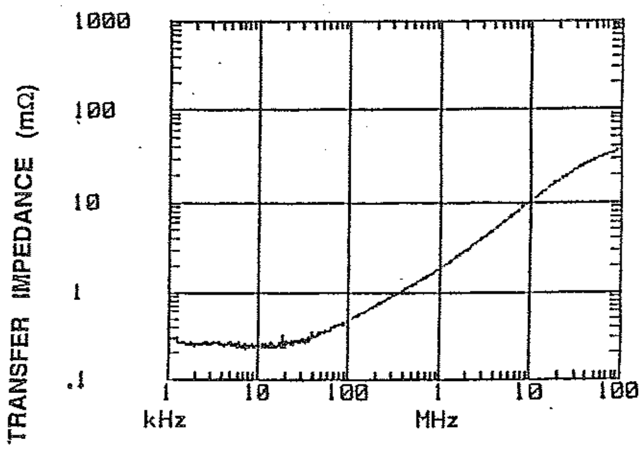

Figure 30. Surface Transfer Impedance of the Second EMI Rack-and-Panel Connector and Backshell without a Gasketted Plug/Backshell Interface.

Figure 31 shows the surface transfer impedance of the second EMI rack-and-panel connector and backshell with a conductive particle filled elastomer gasket installed in the connector plug/backshell interface. Below 1 MHz, the gasket increased the transfer impedance slightly. At 100 MHz, the gasket decreased or improved the transfer impedance by almost an order of magnitude.

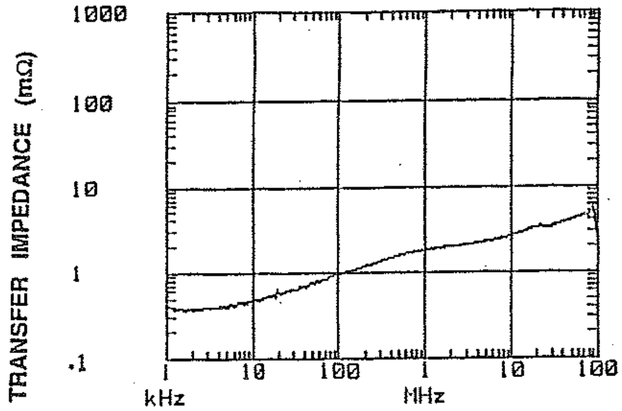

Figure 31. Surface Transfer Impedance of the Second EMI Rack-and-Panel Connector and Backshell with a Conductive Particle Filled Gasket in the Plug/Backshell Interface.

Figure 32 shows the surface transfer impedance of the second EMI rack-and-panel connector and backshell with a sintered stainless steel fiber gasket in the plug/backshell interface. The low frequency performance of this combination is at least as good as the metal-to-metal contact of the ungasketed interface and the high frequency performance is excellent.

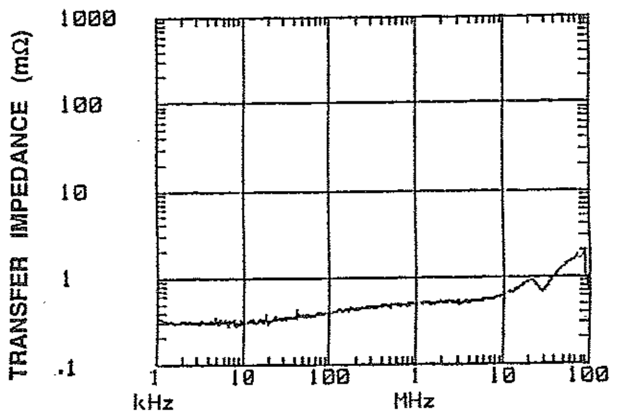

Figure 32. Surface Transfer Impedance of the Second EMI Rack-and-Panel Connector and Backshell with a Stainless Steel Gasket in the Plug/Backshell Interface.

Figure 33 shows the surface transfer impedance of the receptacle/chassis interface. Note that above 1 MHz, the transfer impedance increases and reaches a few milliohms at 100 MHz. Comparison of this measurement with those shown in Figures 29 and 33 indicates that the transfer impedance of the gasketted EMI rack-and-panel connector at 100 MHz is determined by the bond impedance between the receptacle and the chassis.

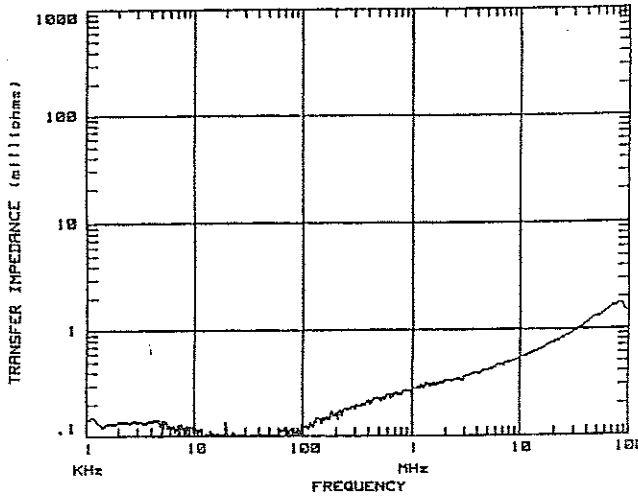

Figure 33. Surface Transfer Impedance of the Receptacle/Chassis Interface of a Rack-and-Panel Connector.

Discussion of Rack-and-Panel Transfer Impedance Measurements

The transfer impedance of the standard rack-and-panel connector at 100 MHz is an inductive impedance of 1 Ω. This is equivalent to an inductance of 1.6 nH. The inductance of the two grounding studs in parallel is only a few factors of two greater than this. This suggests that there is very little contact between the shells of the plug and receptacle.

The measured transfer impedance of the EMI rack-and-panel connector shows that the spring fingers made good contact between the shells of the plug and receptacle. The transfer resistance was generally less than a milliohm. This is comparable with the transfer resistance of circular connectors. Electromagnetic leakage at the plug/backshell interface affected all of the measurements. When coupling through this interface was adequately controlled, such as by the installation of a good gasket, the transfer impedance of the EMI rack-and-panel connect approached that expected of a quality circular connector with a good backshell [6]. Without adequate control of the electromagnetic coupling at the plug/backshell interface, the high frequency shielding performance of the EMI rack-and-panel was severely degraded.

The lack of good mechanical design features, such as the threads of the circular connectors, means that the designer who wishes to produce an electromagnetically shielded rack-and-panel connector has a difficult task. With an adequate design and proper assembly, good performance can be achieved. However, more variation should be expected in the shielding since none of the interfaces can be considered to be ideal.

SUMMARY

Backshell/braid termination assemblies, such as those that use dual cones, typically have a transfer resistance of 0.1 mΩ and a transfer mutual inductance of 10 pH. The latter transfer impedance was almost all accounted for in the few cm of braid included in the sample.

For circular connectors, the backshell barrel and the connector/backshell threaded interface had a transfer resistance of 0.2 to 0.4 mΩ and usually did not display a mutual inductance. The surface transfer impedance of the connector/backshell interface was inversely proportional to the assembly torque. This was particularly evident at the higher frequencies. Torques in the range of 200 in-lbs were required to achieve optimum performance in some cases. Comparison of these measurements with those from a complete connector/backshell/braid termination assembly showed that the plug/receptacle interface should have a low frequency transfer resistance contribution about the same as the braid termination. Its high frequency response appears to be due to contact impedance rather than aperture coupling.

Composite circular connectors have transfer resistances in the range of 7 to 15 mΩ. This an order of magnitude greater than that of metallic circular connectors. At high frequencies, tens of MHz and above, the transfer impedance approaches that of a metallic connector. In this frequency range the shielding performance is determined by the backshell/braid termination interface and the first few inches of the cable braid.

Measurements of the surface transfer impedance of a variety of DB-25 connector/backshell combinations has shown that reasonably good shielding performance (transfer resistances of about 0.5 mΩ and transfer mutual inductances as low as 16 pH) can be achieved if a quality backshell, such as a die-cast backshell with a dual cone or compression insert braid termination, and a dimpled plug is used. The major potential leakage path at low frequencies appeared to be the braid termination. The braid termination that used a strain relief device was significantly worse than one that used a set screw. Circumferential braid terminations provided the best electromagnetic shielding performance. The use of a plastic filled metal mesh gasket under the receptacle degraded the transfer impedance of the connector/backshell assembly by at least a factor of 4 for frequencies less than 100 MHz. A dimpled plug decreased the transfer resistance significantly. At high frequencies, the dimpled plug decreased the transfer impedance by a factor of 3 to 10 (10 to 20 dB). A pigtail braid termination was hundreds of times worse than rather crude circumferential braid termination methods. The best DB-25 subminiature connector/backshell assembly had a transfer resistance that was equivalent to that obtained by a quality circular connector. At high frequencies, however, the DB-25 connector without a dimpled plug was a factor of 5 or 10 worse than a quality circular connector. With a dimpled plug the electromagnetic shielding performance of this connector assembly was almost equivalent to a circular connector

Measurement of the surface transfer impedance of both standard and EMI rack-and-panel connectors from 1 kHz to 100 MHz showed that the standard rack-and-panel connector provides essentially no electromagnetic shielding because it contains no positive mechanism for maintaining electrical contact between the plug and receptacle. Supplementary grounding devices reduce the transfer impedance to desirable levels for frequencies below a few tens of kHz. Electromagnetic shielding at high frequencies is minimal. Spring fingers around the periphery of the plug were very effective for maintaining electrical contact between the plug and receptacle and preventing electromagnetic coupling through the plug/receptacle interface. Control of the electromagnetic coupling through the plug/backshell interface was essential for good high frequency shielding performance. Monel mesh gaskets were electromagnetically effective but cumbersome to install. At 100 MHz, the surface transfer impedance was dominated by the bonding impedance between the receptacle and the chassis. When spring fingers and a gasketed backshell were used, the transfer impedance of the rack-and-panel connector slowing increased from a fraction of a milliohm at low frequencies to several milliohms at high frequencies. This is about equivalent to the electromagnetic shielding expected of a quality circular connector and a good backshell.

CONCLUSIONS

Comparison of the transfer impedance measurements of circular and rectangular connectors show that the shielding performance of rectangular connectors can approach that of circular connectors if supplemental contacts, such finger stock or "dimples," are used to ensure circumferential contact between the plug and receptacle. In addition, quality backshells and circumferential braid terminations must be used in order to achieve optimum shielding performance. Contact impedance is the principal coupling mechanism in circular connectors and usually dominant in rectangular connectors. The high frequency coupling of most connectors is usually equivalent to that through a few inches of single braid. Aperture coupling in the connector is relatively unimportant.

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