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A SIMPLIFIED RELATIONSHIP BETWEEN SURFACE TRANSFER IMPEDANCE AND MODE STIRRED CHAMBER SHIELDING EFFECTIVENESS OF CABLES AND CONNECTORS

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Abstract - The relationship between surface transfer impedance and stirred mode chamber shielding effectiveness proposed by Eicher and Boillot has been simplified. This simplified relationship was used to compare the measured stirred mode chamber shielding effectiveness of nine shielding artifacts with the shielding effectiveness of the same samples calculated from transfer impedance measurements made at lower frequencies or obtained by calculation. For samples with colocated apertures, the relationship predicted the mode stirred shielding effectiveness reasonably well. When the apertures were distributed over a finite length, the relationship predicted mode stirred shielding effectiveness' that were 7 to 10 dB less than those that were measured. This suggests that different relationships must be used for single or colocated apertures and distributed apertures. Above 7 to 10 GHz, the measured stirred mode shielding effectiveness decreases faster than 20 dB/decade. This is probably due to circumferential resonances or resonances within the cable. .

I. INTRODUCTION

Both surface transfer impedance and mode stirred chamber shielding effectiveness attempt to characterize the electromagnetic shielding properties of cables and connectors. Surface transfer impedance measurements become difficult above 1 GHz because of resonances in the test article and in the test fixture. Low frequency mode stirred chamber shielding effectiveness measurements are limited by the need for multiple resonant modes in the test chamber in order to have credible measurements. For practical chambers, mode stirred chamber shielding effectiveness measurement are usually performed above several hundred MHz or 1 GHz. Thus, the two techniques seem to compliment each other. A question that is frequently asked is " Is there a relationship between surface transfer impedance and mode stirred chamber shielding effectiveness that can be used to estimate one from measurements or calculations of the other.

A number of authors have proposed such relationships for single aperture samples and for samples with distributed leakages. In 1991, Eicher [1] compared measurements made with the Matched Triaxial Method (IEC 169-1-3 modified), Mode Stirred Chamber and the Line Injection Method (IEC 96-1) using both flexible cables and solid samples with apertures. He concluded, "In general, some agreement between the three methods can be found in the case of flexible cables. But in view of the data variations, we feel that flexible braided cables like RG58, RG223 types are not suitable for comparison tests at frequencies beyond = 3 GHz (the same restriction applies for connectors with slide-on contacts). The mechanical and electrical condition of the CUT cannot be stabilized to be the same in both test set-up's."

In 1992, Eicher and Boillot [2] proposed mathematical relationships between surface transfer impedance and stirred mode shielding effectiveness for both single aperture samples and samples with distributed leakages.

In 1993 Hill, Crawford, Kanda and Wu [3] derived relationships for the shielding effectiveness of an apertured coaxial line as measured in a stirred mode chamber. Polarizability theory for a circular aperture was used to calculate the coupling through the aperture. Their theory also used averaging over incidence angle and polarization. They compare their calculations of coaxial lines with a single hole with measurements in a stirred mode chamber. Their comparisons of the theoretical and measured shielding effectiveness showed qualitative agreement for the frequency dependence. In general, the theory and measurements agreed within about plus or minus 10 dB. This theory was useful for comparing surface transfer impedance to stirred mode shielding effectiveness because theoretical treatments of both use polarizability theory.

As proposed, all of these relationships were somewhat complex. The present effort attempts to simplify these relationships in order to make them easier to use. This work was performed as part of the work of the P1350 working group of the Standards Committee of the IEEE EMC Society and is the result of contributions by the working group members.

II. THEORY

The starting point for the present analysis was the relationship proposed by Eicher and Boillot [2] for single aperture samples.

$$Z_t^2 + Z_f^2 = 2\, Z_1 Z_2\, 10^{SE/10} \qquad (1)$$

Z_t and Z_f are the surface transfer and capacitive coupling impedances of the sample, Z_2 is the characteristic impedance of the internal system (usually 50 Ω) and Z_1 is equal to 377 Ω. SE is the mode stirred shielding effectiveness of the sample and is equal to 10 log (P_{CUT}/P_{REF}) where P_{CUT} is the power measured from one end of the sample under test and P_{REF} is the power measured by the reference antenna which measures the power density in the stirred mode chamber. Except for sign, this is probably equivalent to the definition of shielding effectiveness used by Hill, et al., namely

$$SE = -10 \log_{10} (A_e/A_r) \qquad (2)$$

A_e is the effective area of the apertured coaxial line ($A_e = P_r/S_d$), A_r is the effective area of the reference antenna, $P_r = P_{CUT}$, and S_d is the incident power density.

The first step in the analysis is to simplify the left side of equation 1. This analysis is primarily concerned with the frequency range where the mode stirred chamber is capable of making meaningful measurements. The lower frequency limit for this frequency range is between 100 MHz and a few GHz depending on the size of the chamber. In this frequency range, the surface transfer impedance is determined by the mutual inductance of the sample's shield. Thus,

$$Z_t = j\omega\, M_{12} = j2\pi f\, M_{12} \qquad (3)$$

M_{12} is the mutual inductance between outside and inside of the cable shield. The mutual inductance is proportional to the magnetic polarizability, α_m, of the aperture in the cable's shield. Consequently, the transfer impedance is proportional to the magnetic polarizability of the aperture in the cable's shield. The capacitive coupling impedance, Z_f, is proportional to the electric polarizability of the aperture in the cable's shield. If the transfer impedance is measured using a test fixture in which the drive line is terminated in the line's characteristic impedance (as is the case in the IEC 96-1 line injection method or a quadraxial test fixture) the measured transfer impedance includes the effects of the electric field coupling factor or capacitive coupling impedancer. Dinallo [4] has shown that the electric field coupling can be included through the use of an effective magnetic polarizability:

$$\alpha_{meff} = (1 + \alpha_e/\alpha_m)\, \alpha_m \qquad (4)$$

In general, and for apertures in particular, the electric polarizability is equal to one half of the magnetic polarizability. Thus:

$$\alpha_{meff} = 3/2\ \alpha_m \qquad (5)$$

Thus, if the surface transfer impedance was measured using a terminated test fixture, the measurement already incorporates the effect of capacitive or electric field coupling. If the surface transfer impedance was measured in a test fixture in which the far end of the drive line was shorted (for example, the traditional triaxial test fixture), the electric field or capacitive coupling can be accounted for by multiplying the measured transfer impedance by 1.5 (adding 3.5 dB). If the surface transfer impedance accounts for both the magnetic and electric field coupling through the aperture, it will be called total surface transfer impedance and will be designated by Z_{total}. The left side of Equation 1 then simplifies to Z_{total}^2.

The stirred mode chamber produces both electric and magnetic fields. Therefore, the stirred mode shielding effectiveness includes the effects of both electric and magnetic coupling.

Substituting Z_{total}^2 for the left side of Equation 1, and solving for the stirred mode shielding effectiveness, one obtains:

$$P_{CUT}/P_{REF} = 10^{SE/10} = Z_{total}^2/(2Z_1Z_2) \qquad (6)$$

After taking the logarithm of both sides, multiplying by 10, and applying the definition of stirred mode shielding effectiveness, Equation 6 becomes:

$$SE = 20 \log Z_{total} - 10 \log (2Z_1Z_2) \qquad (7)$$

Substituting Z_1 = 377 Ω and Z_2 = 50 Ω, Equation 7 becomes:

$$SE = 20 \log Z_{total} - 45.76 \quad \text{(dB)} \qquad (8)$$

Because of the way that Eicher and Boillot defined shielding effectiveness, a good shield will have a SE that is a large negative number. Since Z_{total} is much less than one at the lower portion of the frequency range of interest, the mode stirred chamber shielding effectiveness should be a large negative number (like – 100 dB) at low frequencies and increase (become less negative) with frequency at the rate of 20 dB/decade.

IEC 61000, Part 4, Section 21, Reverberation Chamber Test Methods, Annex F, Screening Effectiveness Measurements of Cable assemblies, Cables, Connectors, Waveguides and Passive Microwave components defines shielding effectiveness as the negative of

Eicher's and Boillot's definition. Hill, et al also uses an equivalent definition. If the IEC definition of shielding effectiveness is used, The stirred mode chamber shielding effectiveness of a sample with a single aperture should be a large positive number at low frequencies and decrease with frequency at the rate of 20 dB/decade. Namely:

$$SE = 45.76 - 20 \log Z_{total} \text{ (dB)} \qquad (9)$$

Examination of the measured stirred mode chamber shielding effectiveness presented by Eicher, Eicher and Boillot, and Hill et al show this type of behavior, at least up to several GHz. At higher frequencies, some of the measurements become frequency independent. If the shielding effectiveness decreased at less than 20 dB/decade, this behavior could be due to losses in the cable. This is generally true for cables with a solid dielectric for frequencies above a few GHz. An alternative explanation may be that the surface transfer impedance of the sample is approaching the characteristic impedance of the measuring circuit and the good shielding approximation is no longer valid. If the measured shielding effectiveness decreases at more than 20 dB/decade, additional coupling mechanisms must be involved.

III. COMPARISON OF SIMPLIFIED RELATIONSHIP WITH EXPERIMENT

The goal of the P1350 Working Group was to develop recommended procedures for constructing shielding artifacts that have known transfer impedance's and shielding effectiveness'. The group constructed two types of such artifacts: Eight 1-m long samples with various hole configurations and an N-type barrel with 2 apertures opposite each other.

III.1 The 1-m Semi-Rigid Coaxial Cable Samples

The first type of shielding artifact consisted of eight 1-m long samples made of two kinds of 50-Ω semi-rigid transmission line. Appropriate N-type connectors were installed at both ends of all the samples. The samples are described in Table 1. The samples can be divided into two sets; each made of one kind of semi-rigid transmission line. Each set contained a solid shield, a shield with two holes opposite one another, a shield with 22 holes spread over 1-m, and a shield with 22 holes spread over 0.33-m.

III.1.1 Measurements

The surface transfer impedance was measured in a quadraxial test fixture and the measured mutual inductance was derived using Equation 3 and the measured transfer impedance at 20 MHz. The measured and theoretical mutual inductance of each of the samples is presented in Table 1. The measured mutual inductance of the samples with apertures compared well with the theoretical mutual inductance (roughly within 10% or 1 dB). The shielding effectiveness was measured in a stirred mode chamber at 1 GHz intervals. The results are shown in Figures 1-7 and the magnitude of the measured stirred mode shielding effectiveness at 5 GHz is included in Table 1. Five GHz was chosen as a frequency where the shielding effectiveness was decreasing at about 20 dB/decade.

Some of the initial measurements are shown in Figure 1. Samples 2 and 2a are 1-m long semi-rigid coaxial

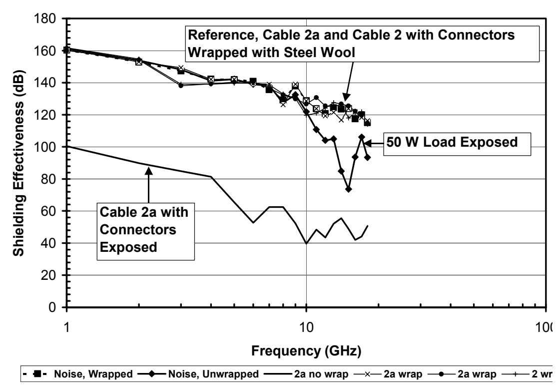

Figure 1. Initial Stirred Mode Shielding Effectiveness Measurements of Samples without Apertures

Table 1. Comparison of Shielding Effectiveness Measured in Stirred Mode Chamber with Shielding Effectiveness Calculated from Surface Transfer Impedance

Sample	Description	Theoretical Mutual Inductance (Henries)	Measured Mutual Inductance (Hoeft)	Measured S.E. 5 GHz Koepke/NIST	Calculated Shielding Effectiveness dB, Theory 1	Calculated Shielding Effectiveness dB, Theory 2	Difference between Measured & Calculated Shielding Effectiveness Theory 1	Theory 2
2	Omni-Spectra Cu Semi-Rigid Solid Dielectric TL, Solid	0	3.97E-13	139.7	83.8		55.8	
2A2	Omni-Spectra AL Semi-Rigid Spiral TL, Solid	0	2.28E-13	140.4	88.7		51.7	
3	Omni-Spectra Cu Semi-Rigid Solid Dielectric TL, Two 5/32"holes	3.16E-11	3.39E-11	41.0	45.2	42.3	-4.2	-1.3
3A	Omni-Spectra AL Semi-Rigid Spiral TL, Two 5/32" holes	2.18E-11	2.08E-11	46.5	49.5	45.5	-2.9	1.0
4	Omni-Spectra Cu Semi-Rigid Solid Dielectric TL, 22 3/32" holes over 1 m	5.47E-11	6.63E-11	47.8	39.4	37.5	8.4	10.3
4A	Omni-Spectra AL Semi-Rigid Spiral TL, 22 3/32" holes over 1 m	3.55E-11	3.52E-11	48.6	44.9	41.3	3.7	7.3
5	Omni-Spectra Cu Semi-Rigid Solid Dielectric TL, 22 3/32" holes over 0.33m	5.47E-11	7.05E-11	46.4	38.9	37.5	7.6	8.9
5A	Omni-Spectra AL Semi-Rigid Spiral TL, 22 3/32" holes over 0.33 m	3.55E-11	3.90E-11	51.2	44.0	41.3	7.2	9.9

transmission line without deliberate apertures. The bottom curve shows the stirred mode shielding effectiveness measured with the connectors exposed. Obviously, there is significant coupling through the cable shield. The second lowest curve is for a noise measurement with only the 50 Ω load exposed. Above 10 GHz, the measured shielding effectiveness decreases significantly indicating some sort of leak. The remaining measurements shown in Figure 1 were made after the connectors were wrapped in steel wool and clamped. The magnitude of these measurements (140 dB) and their frequency dependence suggest that these are truly measurements of the noise floor of the system. All of the remaining measurements were made with the connectors wrapped with steel wool.

III.1.2 Theoretical Calculations

The theoretical mutual inductance was calculated using the spreadsheet program described in [5]. The stirred mode shielding effectiveness was calculated using both the calculated and measured values for the mutual inductance of the apertures. Theory 1 calculated the shielding effectiveness according to Equations 3 and 9 using the measured mutual inductance. Theory 2 calculated the shielding effectiveness using the theoretical mutual inductance multiplied by a factor of 3/2 to account for electric field coupling. The calculated shielding effectiveness values at 5 GHz are presented in Table 1.

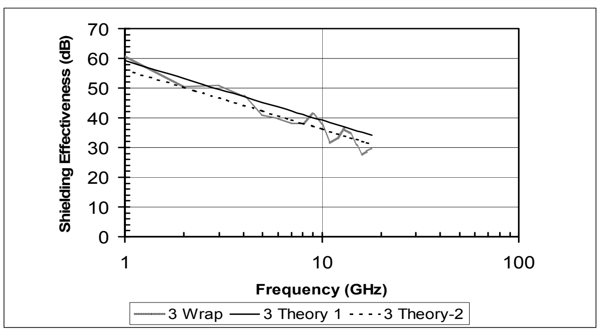

Figure 2. Measured and Calculated Stirred Mode Shielding Effectiveness of Sample 3.

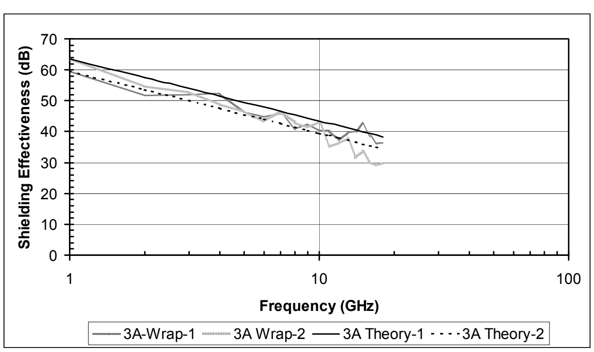

Figure 3. Measured and Calculated Stirred Mode Shielding Effectiveness of Sample 3a.

Figures 2 and 3 compare the measured shielding effectiveness of the 1-m long samples that had only two apertures, opposite to each other, (Samples #3 and #3a) with the shielding effectiveness calculated according to the two methods described previously. This comparison shows that Equation 9 predicts the stirred mode shielding effectiveness with reasonable accuracy over most of the frequency range of the measurements for samples that essentially have a single aperture. Above 10 GHz, the measured shielding effectiveness is beginning to decrease at a rate that is somewhat more than 20 dB/decade.

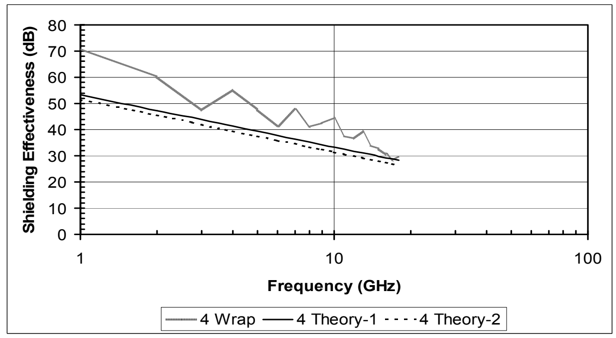

Figure 4. Measured and Calculated Stirred Mode Shielding Effectiveness of Sample 4.

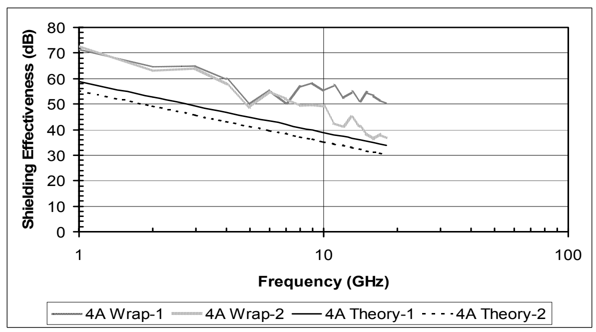

Figure 5. Measured and Calculated Stirred Mode Shielding Effectiveness of Sample 4a.

Figures 4 and 5 compare the measured shielding effectiveness of the 1-m long samples that had twenty two apertures, distributed over 1-m, (Samples #4 and #4a) with the shielding effectiveness calculated according to the two methods described previously. This comparison shows that the predicted stirred mode shielding effectiveness is somewhat less (4 to 10 dB) than the measured shielding effectiveness for samples that have multiple apertures distributed over a finite length of the sample. As in Figures 2 and 3, above 10 GHz, the measured shielding effectiveness is beginning to decrease at a rate that is somewhat more than 20 dB/decade. Although the measured frequency density is too coarse to demonstrate with certainty, the measured stirred mode shielding effectiveness suggests a periodic variation that would correspond to the "summing function" in the equation presented by Eicher and Boillot [2].

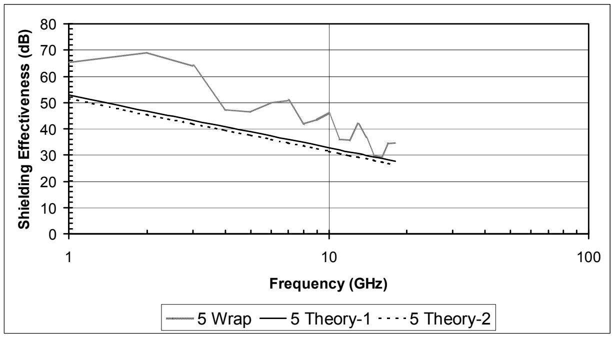

Figure 6. Measured and Calculated Stirred Mode Shielding Effectiveness of Sample 5.

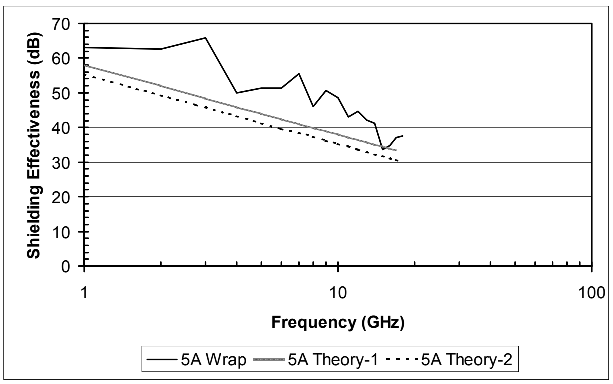

Figure 7. Measured and Calculated Stirred Mode Shielding Effectiveness of Sample 5a.

Figures 6 and 7 compare the measured shielding effectiveness of the 1-m long samples that had twenty two apertures, distributed over 0.33 m, (Samples #5 and #5a) with the shielding effectiveness calculated according to the two methods described previously. In common with samples 4 and 4a, this comparison shows that Equation 9 predicts a stirred mode shielding effectiveness that is less by about 7 to 10 dB than the measured shielding effectiveness. Again, above 10 GHz, the measured shielding effectiveness is beginning to decrease at a rate that is somewhat more than 20 dB/decade. The suggestion of a periodic variation of the shielding effectiveness is also apparent

III.2 The Type-N Barrel with Two Holes

The second type of shielding artifact was a Type-N Female/Female coupling barrel with two 6.35 mm (0.25 in) apertures, opposite to each other.

III.2.1 Measured and Theoretical Shielding Effectiveness

The stirred mode shielding effectiveness of the apertured Type N coupling barrel was measured using the procedures of IEC 61000, Part 4, Section 21, Annex F. The results are presented in Figure 8. The theoretical shielding effectiveness was calculated using Equation 9. The mutual inductance was calculated using a spreadsheet program [5]. The magnetic polarizability was multiplied by 3/2 to account for the electric field coupling. One of the unusual features of this calculation was that the wall thickness was thick enough that the coupling through the hole was reduce by about 10 dB because it acted like a waveguide below cutoff. The results are presented in Figure 8. Examination of Figure 8 shows that the measured shielding effectiveness decreases at the rate of about 25 dB/decade up to about 15 GHz, at which point the shielding effectiveness decrease more rapidly.

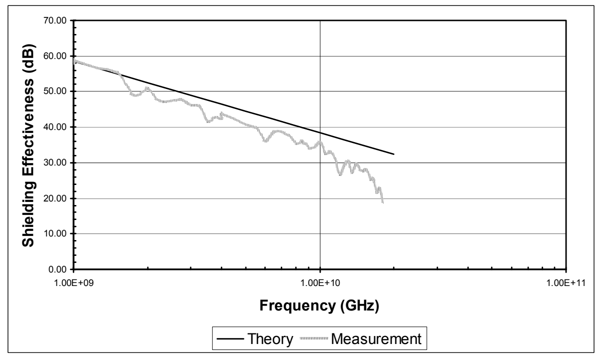

Figure 8. Measured and Calculated Stirred Mode Shielding Effectiveness of Type N Barrel with Two Apertures

The increase in the rate at which the shielding effectiveness decreases above about 10 GHz is seen, but not explained, in measurements other than those reported here [1, 2, 3]. It cannot be due to absorption because it is a reduction rather than an increase in the shielding effectiveness. A possible explanation is as follows. The current in the present and referenced analyses is assumed to be flowing longitudinally along the sample. This is undoubtedly true below 10 GHz. At a high enough frequency, the sample can resonate in the circumferential direction. Broyde [6] has defined transfer functions for these non-normal coupling modes. In simple terms, a circumferential current would not couple to the core of the coaxial cable since the voltage source is orthogonal to the core. The surface electric field, on the other hand, is always perpendicular to the surface of the cable shield. This charge density induces a current onto the core of the cable that shows up as a voltage on the ends. An increase in the current density will increase this voltage and reduce the shielding effectiveness. The question remains, "Does this occur in the frequency range in question?" The circumferential resonance should occur when the circumference of the sample is a half wavelength. Thus a Type-N barrel with an outer diameter of 16 mm should have a circumferential resonance at about 3 GHz. This is somewhat low to explain the decrease in the measurements. The inside of the barrel is 7.14 mm. This should resonate at 21 GHz. A resonance at this frequency would be consistent with the observed decrease in the shielding effectiveness. This type of resonance is also consistent with the measurements of Eicher and Boillot [2] which showed that the larger the diameter of sample, the more the shielding effectiveness above 10 GHz was reduced

IV. SUMMARY

The relationship between surface transfer impedance and stirred mode chamber shielding effectiveness proposed by Eicher and Boillot has been simplified. This simplified relationship was used to compare the measured stirred mode chamber shielding effectiveness of nine shielding artifacts with the shielding effectiveness of the same samples calculated from transfer impedance measurements made at lower frequencies or obtained by calculation. For samples with colocated apertures, the relationship predicted the mode stirred shielding effectiveness reasonably well. When the apertures were distributed over a finite length, the relationship predicted mode stirred shielding effectiveness' that were 7 to 10 dB less than those that were measured. This suggests that different relationships must be used for single or colocated apertures and distributed apertures. Above 7 to 10 GHz, the measured stirred mode shielding effectiveness decreases faster than 20 dB/decade. This is probably due to circumferential resonances or resonances within the cable. .

V. ACKNOWLEDGMENT

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