Electromagnetic Noise Reduction Strategies for Cable Systems

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Abstract—**This research is representative of a two semester project focusing on noise reduction strategies for cable systems. Several specific areas of EM noise reduction are evaluated including shield termination techniques, and double shield techniques. In obtaining empirical results for all test cases, noise injection through bulk current injection (BCI) and transverse electromagnetic (TEM) cell exposure is utilized. After discussing the results of these experiments, a short case study will be presented by which noise reduction techniques are implemented and evaluated.**

I. Introduction

A. Basic Terminology and Concepts

The comprehension of practical electromagnetic noise reduction strategies is essential in designing electronic systems that operate as intended. If not designed properly, the system can suffer from adverse effects of noise. Electronic noise can be defined as any unwanted electromagnetic (EM) energy that couples into a system. Thus, if you are able to prevent the EM energy from coupling into the system then you are able to (theoretically) eliminate the noise. Realistically one aims to minimize the coupling of energy to an acceptable level. It will be shown that some noise reduction strategies are more effective than others in reducing the level of coupled energy.

An electronic system can be subjected to EM noise in two ways – conducted or radiated. Conducted susceptibility relates to electromagnetic energy that is directly introduced into an electronic system by a physical connection to power or signal conductors. Radiated susceptibility relates to electromagnetic noise that is introduced through radiated sources external to the electronic system. It is important to point out that both the BCI and TEM cell techniques discussed in this paper test the electronic system's radiated susceptibility characteristics.

Shielding is an important method for protecting conductors against EM energy. A shield can be defined as any material that protects a device or cable from electric, magnetic, or plane wave energy. This shield can be a solid conductor (foil), or can be comprised of many finer interwoven wires (braid). A braided shield is commonly referred to as overbraid when it is manufactured separate of a cable (thus being able to pull it over the exterior jacket of a cable).

For aerospace or military purposes, cables are often terminated through the use of connector-backshell assemblies. Since the connector and backshell are usually responsible for terminating the shield, it is crucial that this hardware offer a low impedance path. In addition to terminating the shield, the backshell also offers strain relief for the cable.

Fig. 1 D38999 Connector with Standard Backshell

Figure 1 shows a D38999 connector (left) with a standard backshell (right). For our experiments, cables with pigtail connections utilize this type of backshell.

Fig. 2 D38999 Connector with EMI 360 Backshell

Figure 2 pictures the same D38999 connector with an EMI 360 backshell. This backshell offers additional shielding protection since the shield can be terminated in a full circumferential manner.

B. Basic Field Theory

In order to predict the relative effectiveness of different shielding and termination techniques, it is important to understand the ways in which electromagnetic fields interact with a shielded cable. This interaction is highly dependent on the quality of the shield and the technique used to terminate it [1],[3],[8]-[11]. For this purpose, a basic level of field theory is needed.

From this theory, the electromagnetic wave impedance can be defined as the magnitude ratio of E_θ to H_ϕ, or ($Z_W = E_\theta/H_\phi$). For far field conditions ($r \gg \lambda/2\pi$) the wave impedance is simply $Z_O = \frac{E_\theta}{H_\phi} = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 377\ \Omega$. Figure 3 shows a graph of the wave impedance vs. distance. Notice the two separate curves in the near field region for the lower impedance magnetic field and high-impedance electric field.

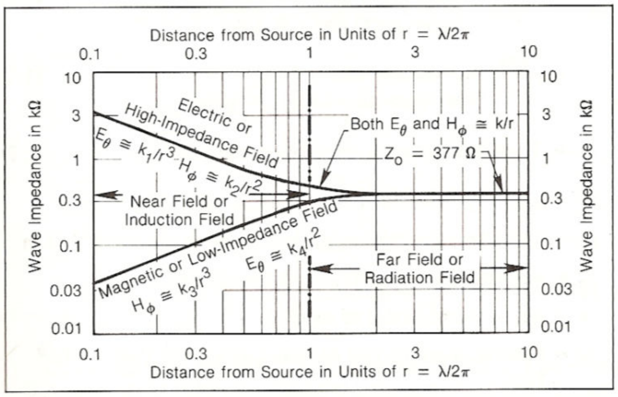

Fig. 3 Wave Impedance vs. Source Distance [9]

An impinging EM field can either be absorbed or reflected by the shield of a cable (often a combination of both). For the field to be reflected an impedance mismatch must exist between the wave impedance and the barrier impedance of the metallic shield. For far field conditions, a cable shield is expected to equally reflect both an E-field and H-field. However, for near field conditions, a shield must exhibit extreme conductivity to reflect an impinging H-field while even a mediocre conductor will provide acceptable E-field reflection.

Absorption can also be beneficial in effective shielding when frequencies are high enough for the skin effect to occur. At frequencies where this phenomenon occurs, noise current does not penetrate the shield material and therefore is isolated from the protected conductors found within the shield. Since the skin effect is paramount to absorption, it is important to note that at low frequencies (typically f < 1 MHz) the primary performance of a shield would be due to reflection [9].

C. Literature Review

Electromagnetic compatibility (EMC) has long been a topic of discussion and research. While many sources [1],[3],[8]-[11] give guidelines for noise reduction there seems to be a lack in comprehensive empirical results that yield convincing proof for many recommendations. One of the most respected books on the subject, Ott's *Noise Reduction Techniques in Electronic Systems* provided an excellent starting point for our investigation. As a point of comparison, all of Ott's experiments were repeated with our test setup to verify that similar results were obtainable. One notable improvement from Ott's experimental setup is our ability to vary the test frequency from values of 50 kHz to 400 MHz (where Ott only tested at 50 kHz) [5].

Another unique resource discovered during literature review was a publication by Trout [7]. Her publication emphasized bulk current injection's validity as compared to parallel plate noise injection when testing cable susceptibility.

II. Single Shield Terminations

A. Experimental Setup

Both single shield and double shield experiments were conducted with the same electronic system, consisting of two Hammond shielded electrical enclosures, one containing the source resistance (50Ω), and the other containing the load resistance (1MΩ). The boxes were mounted on a large aluminium plate acting as the system chassis. Cables connecting the two boxes measured 50 cm in length and were attached to the boxes using D38999 military-style connectors. An instrumentation cable also connects to the load box with a D38999 connector that allows for measurement of noise voltage across the load resistance.

Paramount to the design of this experimental setup was the ability to create an environment that provided reproducible results. To ensure that measured outcomes were representative of experimental parameters and not setup variance, the following parameters were kept constant among comparable experiments (unless specifically studying the effect of the variance):

- EM field levels and patterns
- Connectors
- Cable routing
- Chassis
- Shield connections
- Wire characteristics (manufacturer, gauge, shield material, coverage, impedance, etc.)

Two general types of noise signals, a sinusoid and pulse wave, were used in both the TEM cell and BCI experiments. . When determining shielding effectiveness at specific noise frequencies, the sinusoidal wave was utilized. In order to carry out the single noise spectra experiments LabVIEW was employed to control the HP8657B RF Signal Generator in combination with the Agilent 54401B spectrum analyzer using GPIB (General Purpose Information Bus) protocol. Interfacing control of the instruments through LabVIEW allows for an automated sweep of the signal generator from 50 KHz through 400 MHz. At each commanded frequency, the program records the resulting noise signal from the spectrum analyzer and records the frequency and noise levels in a file. Through the utilization of the LabVIEW program, an increase in the efficiency and speed of the automated data taking allowed many more data points to be taken when compared to the alternative of manual equipment control.

The second type of noise signal used is a pulse wave. While the sinusoidal noise signal is valuable for understanding noise reduction characteristics at singular frequencies, a more

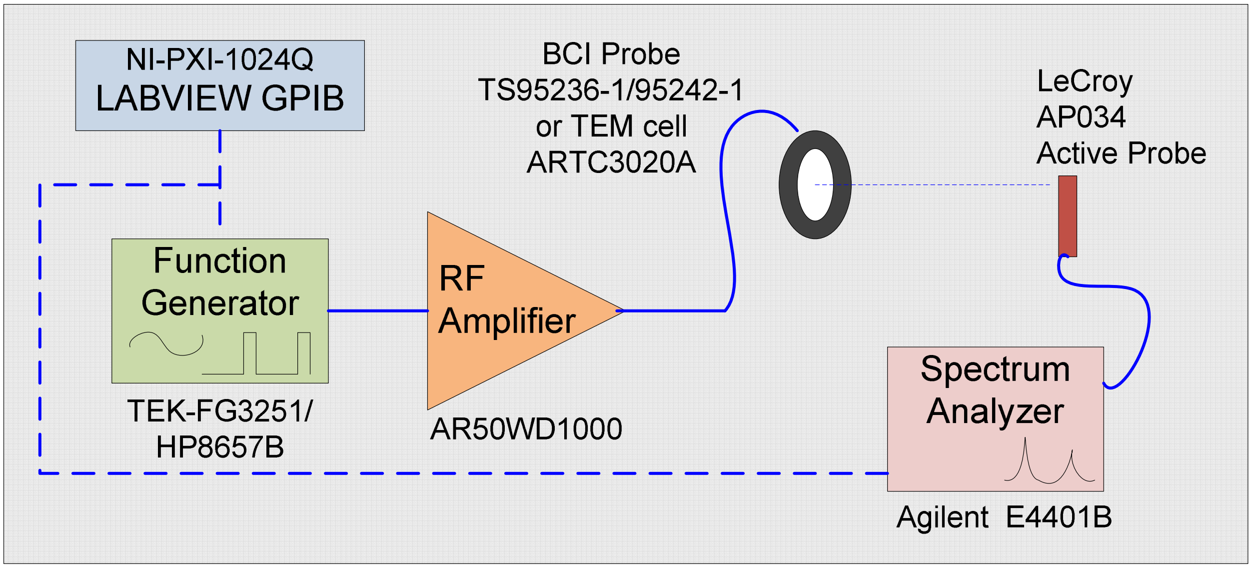

Fig. 4 Equipment Interconnection Diagram for Experimental Setup

practical determination of overall shielding effectiveness is found from a broadband noise signal. A pulse wave was chosen as a good candidate for this broadband noise source since the frequency spectrum is easily understood. The signal specifically used in all experiments was a periodic pulse of 5 MHz, 2.5 ns rise/fall times, and a 4 ns pulse width.

When injecting the square pulse wave, the Tektronix AFG3251 Arbitrary Function Generator is used. This generator was not interfaced with the LabVIEW GPIB program since it was more efficient to maintain local control of all equipment during the broadband noise experiments. For the broadband noise (square pulse wave) injection tests, the total induced noise power is measured by the spectrum analyzer instead of the singular peak amplitudes. In order to calculate the channel power, the spectrum analyzer simply integrates the noise signal it sees over the range that the user specifies. To acquire accurate data it was found that the large span (50KHz – 400 MHz) had to be broken down into four integration windows (0-100, 100-200, 200-300, 300-400MHz). Smaller windows allow the spectrum analyzer to achieve the necessary signal resolution for accurate results.

As seen in Fig. 4, both signal generators have their outputs amplified through the AR50WD1000 RF Amplifier. After amplification with a gain of about 48 dBm, the signal is routed to either the BCI probe (ETS95236-1/95242-1) or the TEM cell (ARTC3020A) depending on the signal type. In all test cases, an active differential probe (LeCroy AP034) is connected across the load (through the instrumentation cable) to sense the load noise signal and convey the information to the spectrum analyzer where further processing is done. A differential probe is specifically chosen to allow for flexibility in floating the grounding scheme of the test circuit.

As shown in Fig. 6, the AR TC3020A TEM cell provides an environment where the entire electrical system can be exposed to radiated transverse electromagnetic fields – emulating far field exposure. To achieve meaningful and reproducible data from TEM-cell experiments, two criteria were set.

1. Radiated field patterns and levels remain same throughout all tests.
2. Noise coupled into the cable (the experimental variable of interest) must dominate the inherent noise coupled through the test setup.

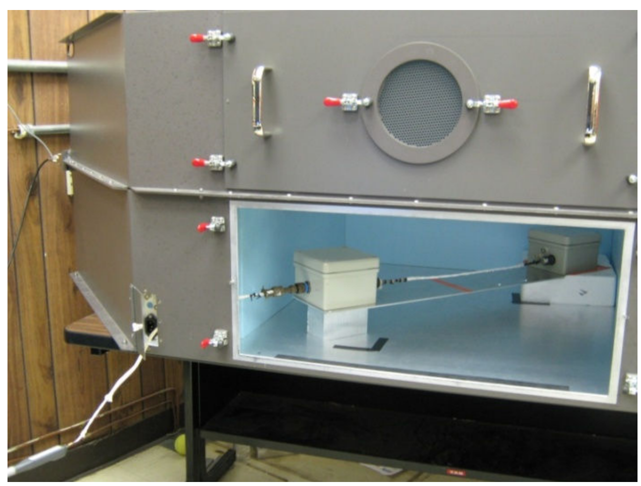

Fig. 5 TEM Cell test setup with electronic system

The first criterion is met by fixing the position of the electronic system in the TEM cell and maintaining the same noise signal level for all tests. The second criterion is achieved by ensuring the electronic system is properly grounded, and the cable relaying the measured signal is short in length and carefully shielded. For our experiments, the electronic system is grounded on the load end through an aluminium block to the TEM cell ground plane while floating the source end of the system with a Styrofoam spacer. This ensures that there is no ground loop between the TEM cell ground plane and the aluminium chassis of the electronic system. To further minimize noise coupling into the measurement cable, an overbraid is installed over the cable and terminated into both the EMI 360° backshell of the connector (grounded to the load box of the electronic system) and the TEM cell ground plane (as the cable exits the TEM Cell enclosure).

As shown in Fig. 11, BCI probes ETS95236-1/95242-1 were used to inductively couple signals over the frequency range of interest (50 kHz – 400 MHz). Due to the local nature of field exposure with the BCI method (versus the broad field exposure for the TEM Cell experimental setup), the design requirements as specified for the TEM cell can also be met for the BCI method with little trouble. The first criteria is met by keeping excitation signal levels constant through comparable tests, criteria two is met by placing the BCI clamp in the middle of the test cable.

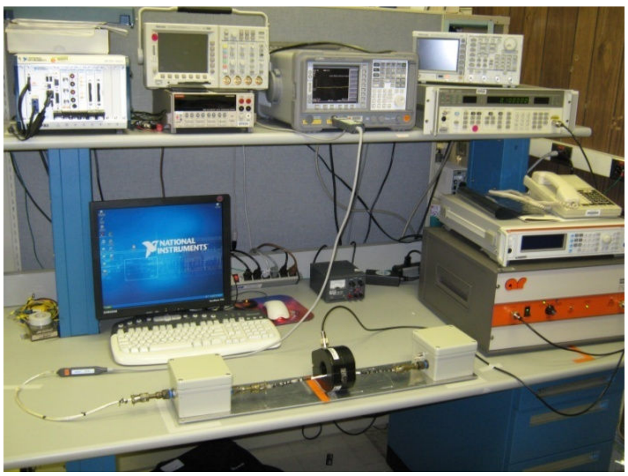

Fig. 6 BCI test setup with electronic system

B. *Termination Geometries and Materials*

Cable shielding often plays a crucial role in protecting electronic systems against unintentional radiation and reception of EM interference. It is well understood (although the methods are not always agreed upon) that proper shield termination significantly affects the shielding effectiveness [1], [3],[8]-[11]. Not obvious is to what degree parameters such as termination geometry and material have on shielding performance. It is not the goal of this particular study to investigate single-ended versus two-sided shield connections as this has already been reported [1]. Rather, this research focuses on shield geometries and materials from a practical standpoint.

Two predominant termination geometries are 360° and single-point. Single point terminations, such as pigtails or drain wires, suffer from several shortcomings. First, they force shield current to flow in an asymmetrical manner yielding higher transfer impedances. The unshielded wiring (and associated loop) also acts as a receptor and/or radiator of noise. One would therefore predict that the pigtail termination (the only single point termination method tested in this study) would underperform the 360° terminations.

Full 360° shield termination may be defined as any method that terminates the shield in a circumferential manner – that is no length of the cable left exposed even as it enters the connector. Examples of 360° termination geometries that were tested, include:

- cable shield expanded over an EMI backshell,
- copper tape connecting the cable shield to a standard backshell,
- overbraid secured to the cable shield and a standard connector,
- overbaid secured to the cable shield and an EMI backshell.

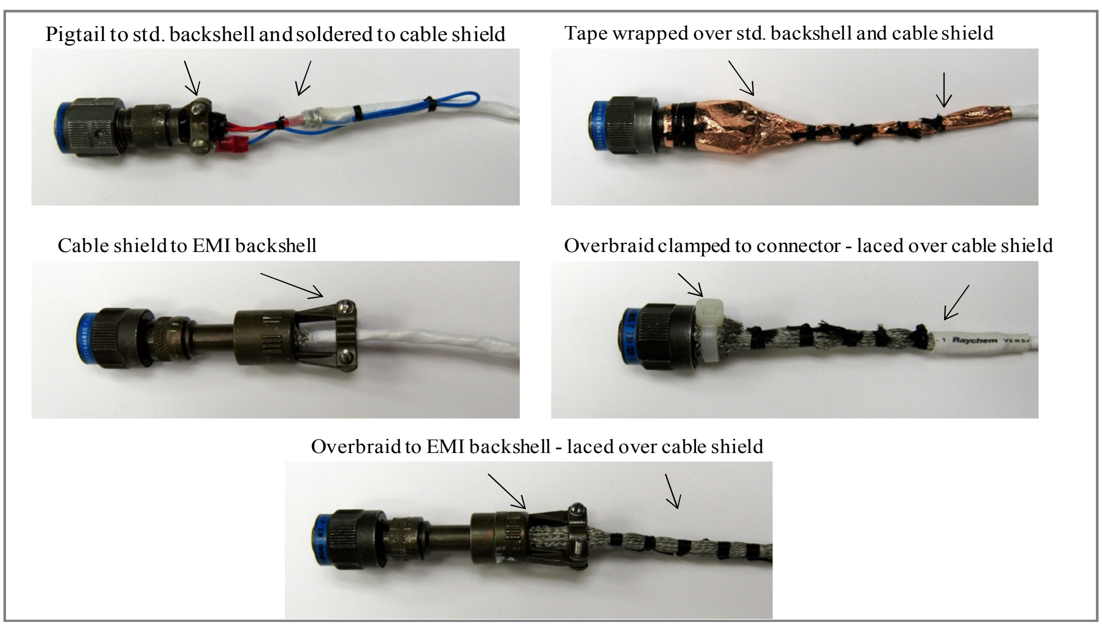

Fig. 7 Shield terminations

One would expect that any high conductivity, non-ferrous material of adequate thickness (greater than skin depth) would offer comparable shielding. Our investigation used three materials: the cable shield itself (MIL-W-1687817), shielding overbraid (RG 174), and conductive foil tape (3M 1245). In all cases, care was taken when building the cables to ensure solid mechanical and electrical contact between all conductive surfaces. Fig. 7 shows the terminations tested, where both ends of the cable are terminated in the same manner.

Fig. 8 illustrates the schematic for our electronic system. Both ends of the shield are terminated to the chassis of the electrical system through Z_1, Z_2. As seen from later results, the inherent impedance of each type of termination affects the shielding effectiveness of the cable. Each circuit is also grounded to chassis with the noise voltage being measured across the load resistor.

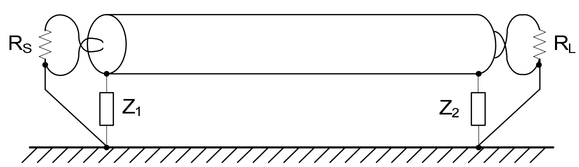

Fig. 8 Shield Termination Impedances for Twisted Shielded Pair

C. TEM Cell Experimental Data—Single Shield

It has been shown in a previous study that pigtail shield terminations are generally less effective than EMI 360° backshell terminations [1]. One would therefore expect that all of the 360° termination methods would show improvement in shield performance over the pigtail case. Of greater interest however is how the different methods of achieving the 360° affect the shielding effectiveness.

Figures 9 and 10 show the results from TEM-cell testing of the five different termination types. Across the majority of the test frequency range, the pigtail termination is approximately 30dB worse than all other types. It is interesting to note that there is little difference in shielding performance between any of the 360° termination methods. This is significant, because it suggests that the use of non-optimal 360° terminations (e.g. conductive tape) as can be effective alternatives.

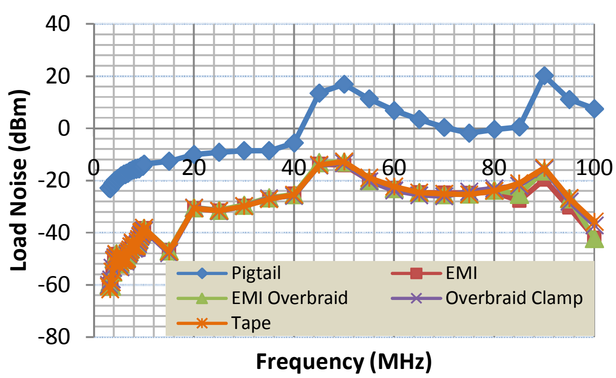

Fig. 9TEM-cell-shield termination effectiveness (3 – 100 MHz)

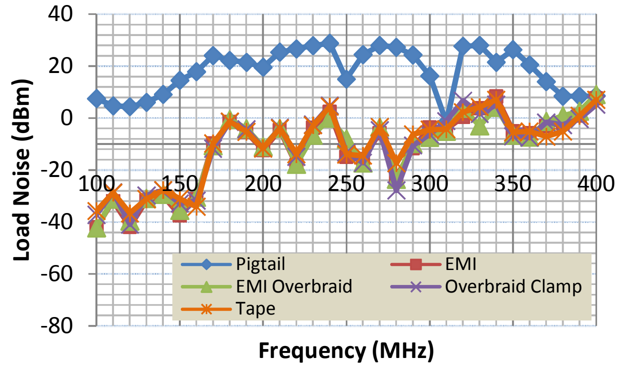

Fig. 10 TEM-cell tested shield termination effectiveness (100 – 400 MHz)

D. BCI Experimental Data—Single Shield

As shown in Fig. 11, the results from BCI testing are similar to that from the TEM cell for the comparable rage of 3 MHz to 400 MHz. BCI testing demonstrates that all the 360° terminations exceed that of the pigtail by approximately 40 dB.

In utilizing inductive coupling, BCI testing allows the effects of much lower noise frequencies to be measured. In our particular study, testing at lower frequencies better emphasizes the resistive component of the shield termination impedance (except for the tape terminated cable, as later explained). The shielding effectiveness at lower to midrange frequencies (0.05 – 25 MHz) is given in Fig. 12.

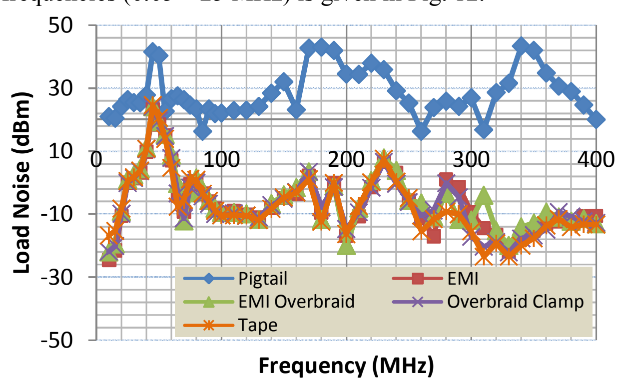

Fig. 11 BCI-tested shield termination effectiveness (0.05 – 400 MHz)

The best performing cables (from 50 kHz to 5 MHz) listed in order of shielding effectiveness are: EMI overbraid, EMI, overbraid tied to connector, conductive tape, and pigtail. It is interesting to note that the conductive tape-terminated cable performs approximately 10 dB worse than the other tested 360° terminations for this frequency range. After 5 MHz this difference decreases, until the tape-terminated cable is approximately equal in effectiveness at about 20 MHz. This phenomenon can be explained when the actual geometry and properties of the tape termination are considered.

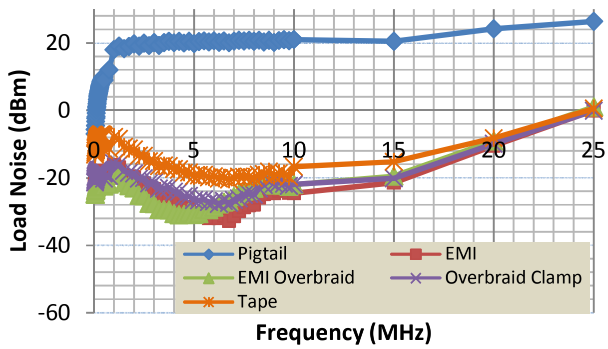

Fig. 12 BCI-tested shield termination effectiveness (0.05 – 25 MHz)

Geometrically, the tape is spirally wound with overlapping turns around the cable shield and connector backshell. While these turns make electrical contact, there still exists some capacitance between each layer of overlapped foil due to the adhesive. This finite capacitance forces lower frequency shield current to flow spirally through the tape termination creating a mutual inductance between the tape termination and the shielded conductors within. At around 20 MHz, the capacitive reactance is small enough to effectively short the turns of the tape. This causes the copper tape to electrically look more like a 360° conductive cylindrical shield [3].

E. *Broadband Data—Single Shield*

Unlike the swept single-carrier data presented in sections *A.-C.,* the following data is obtained through driving the TEM cell and BCI probes with a broadband signal (periodic pulse of 5 MHz repetition rate, 2.5 ns rise/fall times, and 4 ns pulse width). The narrow pulse width and short rise and fall times create a broadband distribution spectral energy.

The broadband results for both TEM-cell and BCI testing are given in Table I. Once again there is a clear distinction between effectiveness of the pigtail and 360° terminations. Once again, all of the 360° termination methods yielded nearly identical shielding properties to the net broadband energy.

TABLE I
BROADBAND NOISE INJECTION-SHIELD TERMINATION METHODS

Cable Type	**TEM (dB)**	**BCI (dB)**
Pigtail	-7.10	1.26
EMI	-24.58	-17.68
EMI Overbraid	-25.31	-17.68
Overbraid bonded	-24.47	-17.98
Tape	-24.24	-17.68

III. Double Shield Terminations

In situations where additional EM protection is needed, double shielded cables can be employed. Other authors have concluded that two braided shields can help to reduce noise coupling by 20 to 30 dB [3]. While it is not our intention to compare single shield effectiveness against double shield effectiveness we do wish to compare the relative effectiveness of three specific double shield termination strategies as shown in Table III.

TABLE II
DOUBLE SHIELD TERMINATION CABLE TYPES

	Description
SS_SS	Outer and inner shields are terminated to the EMI 360 backshell with overbraid.
SO_OS	One end of the cable has the outer shield terminated to EMI 360 backshell with overbraid, and the inner shield is left unterminated. Opposite end of cable has the outer shield unterminated and the inner shield terminated to EMI 360 backshell with overbraid.
S.TP_S.TP	Outer shields are terminated to EMI 360 backshell with overbraid, and the inner shields are terminated to a quiet ground on the source/load circuits using a through pin connection

It is important to note that all three cables were made from the same double shielded double jacketed stock cable (Blake M27500-22-NE-2-A72) using identical connectors, EMI 360 backshells, and overbraid.

A. *TEM Cell Experimental Data—Double Shield*

When predicting the effectiveness of each of the three cable types, it is important to notice that the SS_SS and S.TP_S.TP cables have shields tied to chassis at both ends. At low frequencies, the SO_OS cable will prevent the flow of shield current. However at higher frequencies, it should act similar to the shorted cables because the capacitive coupling will provide an effective short between the shield layers.

This predicted behaviour is evident in Fig.'s 13 and 14 as the SO_OS cable provides about 45 dB less protection when compared to the SS_SS and S.TP_S.TP cables. This trend continues until approximately 150 MHz where the noise frequency is sufficient to allow for capacitive coupling in the SO_OS cable. While not necessarily evident from Fig. 10, there is a 4 dB improvement of the S.TP_S.TP cable over the SS_SS cable until around 30 MHz. After this crossover frequency it seems that the S.TP_S.TP cable performs slightly worse than the SS_SS. This data would suggest that for frequencies below 10-30 MHz, there is a slight advantage to routing the inner shield through a pin to an internal system ground. That advantage is reversed at higher frequencies.

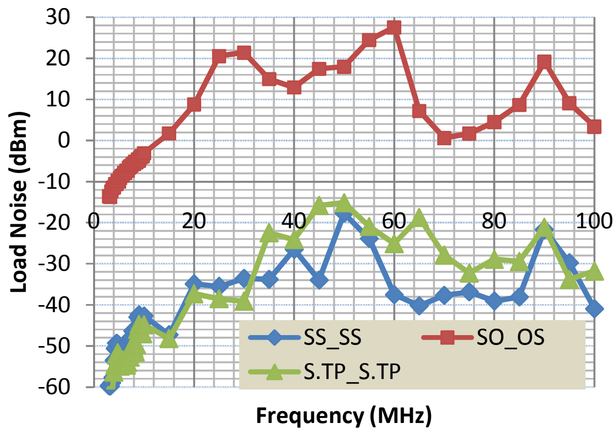

Fig. 13TEM Cell-Double Shield Effectiveness (3– 100 MHz)

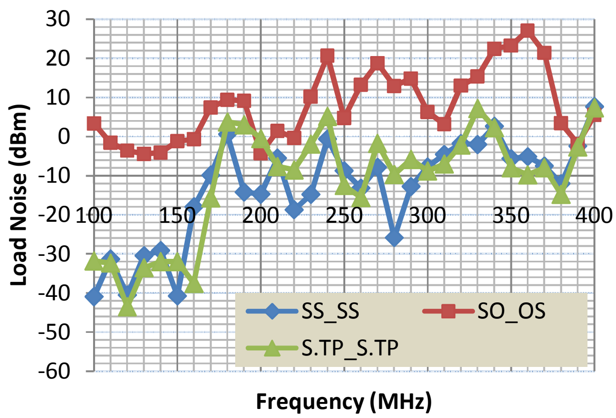

Fig. 14 TEM Cell-Double Shield Effectiveness (100– 400 MHz)

B. *BCI Experimental Data—Double Shield*

Bulk current injection testing yields comparable results as seen in Fig.'s 15 and 16. In this test, the SO_OS cable also performs worse at lower frequencies. Also similar to the TEM cell data is the 4 dB improvement of the through pin cable versus the SS_SS cable until around 30 MHz, after which no consistent benefit is realized.

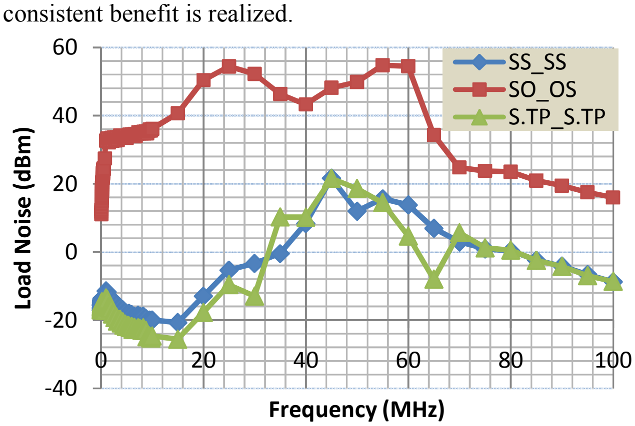

Fig. 15 BCI-Double Shield Effectiveness (0.05– 100 MHz)

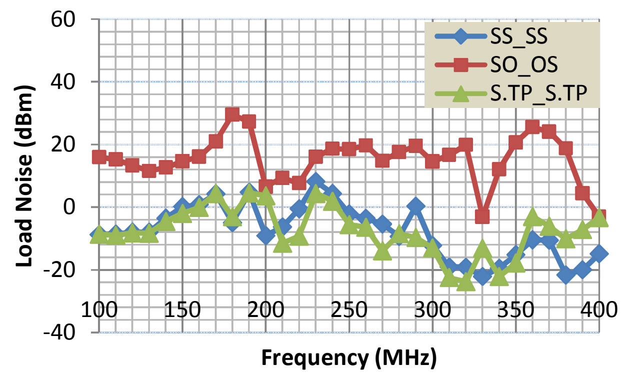

Fig. 16 BCI-Double Shield Effectiveness (0.05– 400 MHz

IV. Model Aircraft Case Study

A. *Problem Description*

Pilots of a particular research model aircraft reported loss of a safety-pilot backup radio control link during multiple flights. Fortunately the uplink and downlink from the mobile operating station to the aircraft was not disturbed to allow for the safe landing of the aircraft. Further investigation revealed two other symptoms. First, the link failure occurred repeatedly after the aircraft had flown a relatively short distance (compared to the expected range) away from the location of the ground safey-pilot. Secondly, some of the control surfaces exhibited an undesirable jitter movement.

B. *Hypothetical Diagnosis*

It was hypothesized that electromagnetic interference from the onboard research system was to blame for the safety-pilot control link failure. This conclusion was drawn in part from the fact that this loss of link was directly related to the transmitter to receiver (safety pilot on ground to aircraft) distance. Thus, the range of the aircraft was severely limited indicating the signal to noise ratio at the receiver was unacceptable. The last symptom leading to the conclusion of EMI problems was the inherent jitter in many of the control surface servos. This could indicate that there is a noisy feedback to the flight controller.

C. *Determination of Appropriate Noise Reduction Strategies*

Before treating the symptoms of this alleged EMI problem, the source of the noise first needed to be determined. An obvious first guess was the servos. In an attempt to understand the nature of their operation, an experiment was conducted that involved the viewing of the noise voltage across the power terminals of the JRDS8411 with an active probe and oscilloscope. From the initial analysis of the resulting waveform it became apparent that the servo motors were indeed a source of noise as transients with magnitide 0.44 volts were observed on the oscilloscope. In attempting to limit these transients a shunt capacitor with low effective series resistance (ESR) was installed across the power terminals of the servo. It was determined this action cut the noise voltage by approximately half. Table III is populated from additional experiments where the noise voltage across the power terminals of the servos was measured before and after installation of a shunt capacitor.

TABLE III
MODIFIED VS. UNMODIFIED SERVO NOISE VOLTAGE

Servo Model	Shunt Capacitor	Noise (dBmV)
JRDS8411	No cap	32.9
JRDS8411	w/150uF cap	27.6
JRDS3421	No cap	32.5
JRDS3421	w/150uF cap	24.1
JRDS168	No cap	32.0
JRDS168	w/100uF cap	29.5

One possible source of the servo jitter may have been noise coupling into the feedback (position sensor or potentiometer) of the control system. To protect against this coupling of noise, a shielding experiment was conducted to determine the best configuration for the shield terminations. A diagram indicating the possible shield terminations is shown in Fig. 17. Figure 18 provides the results of the experiment. It is clear from this figure that the S-S configuration (shield shorted at both the potentiometer ground and the enclosure) will provide the maximum protection against electromagnetic interference.

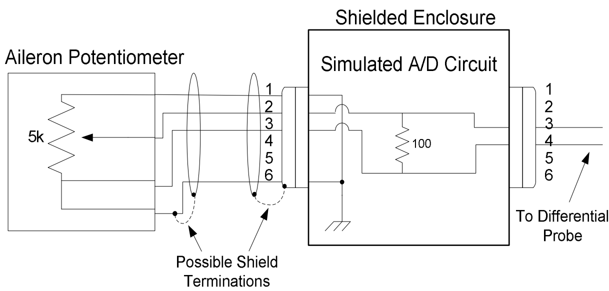

Fig. 17 Potentiometer Cable Shielding Diagram

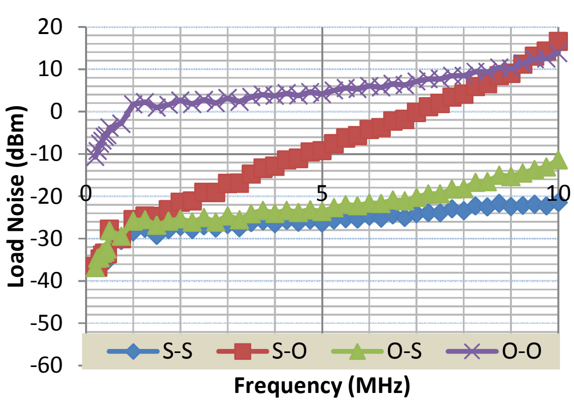

Fig. 18 Potentiometer Cable Shield Effectiveness (0.2– 10 MHz)

V. Conclusions

A. *Single Shield Terminations*

Many options exist for shielding termination, including pigtails, overbraid, and conventional 360° EMI backshells. Although it has long been known that pigtail shield connections underperform 360° termination methods, our experiments indicated that pigtails were typically worse by more than 35 dB for frequencies above a few MHz. This would indicate that one should avoid terminating shields with pigtail connections. However if a pigtail termination is to be used, shortening the pigtail wire length and minimizing exposed wiring has been shown to slightly improve the noise rejection capabilities of the cable [1].

All TEM cell and BCI data suggest any of the four tested 360° shield termination techniques provide comparable protection for frequencies above 20 MHz. This is primarily due to the circumferential nature of all terminations where virtually no exposed wiring exists and inductive effects are minimized. However, from 50 kHz to 20 MHz BCI testing indicates that a foil tape shield termination is less effective (as much as 10 dB) when compared to the other 360° terminations. This may be related to both the mutual inductance between the tape and inner shielded conductors and the finite capacitance between the layers of the tape.

B. *Double Shield Terminations*

When single shielded cable assemblies do not provide the necessary EMI protection, double shielded cables can yield additional noise rejection capabilities [3]. Of the three tested double-shield configurations, the S.TP_S.TP cable performed the best at frequencies below 30 MHz, above which it was slightly inferior to the SS_SS cable. The SO_OS cable offered significantly less protection, and in general should only be used when preventing dc shield current is a necessity (i.e. worried about low-frequency ground loops).

C. *TEM cell vs. BCI Injection Methods*

Comparing the results from the TEM cell and BCI methods(for the single and double shield experiments), both methods yielded very similar results for our simple electrical system. This high degree of correlation would lead to the conclusion that both methods are valid when testing for cable susceptibility up to a few hundred MHz. Bulk current injection has the additional benefit of being able to couple EM energy into a system at lower frequencies. However this method constitutes a local inductive injection of noise and does not always accurate reflect the benefits if shielding against electric fields. TEM cell exposure subjects an entire electrical system to true far-field radiated emissions, at the expense of size restrictions and more complicated test setup requirements.

D. *Case Study*

When troubleshooting a noisy system such as the model aircraft it is helpful to identify the source(s) of noise and try to limit the sources ability to radiate or conduct emissions. This approach was taken in this case study as the servo motors themselves were identified as sources. After identifying that they were indeed sources, steps were taken to minimize the amount of emissions through the use of low ESR shunt capacitors. As seen in Table III, these capacitors helped to significantly reduce the noise voltage.

After minimizing the emissions of the offender, the receptors were analyzed. In this particular case the potentiometers for every control surface posed a significant risk as receptors since they were initially unshielded and provided feedback into the flight control system. By evaluating the possible ways of terminating the shield the highest level of protection is ensured. Thus, the shield will be terminated at the potentiometer end and the flight telemetry (A/D enclosure) end. With the results from these experiments a better understanding of appropriate solutions was obtained. Hopefully with these and additional measures the problem of safety-pilot link failure will be solved

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