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LOW FREQUENCY SHIELDING OF AN
EXPERIMENTAL MULTIWIRE CABLE

Metrology Engineering Project
Report, MEP 74-76

D. W. Stone, Project Leader

Published January 1976

MASTER

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Department 142

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LOW FREQUENCY SHIELDING OF AN EXPERIMENTAL MULTIWIRE CABLE

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Prepared by D. W. Stone, D/142.

Shielding tests were conducted on an experimental cable and on four types of magnetic-shielding materials. Some of the manufacturing techniques of this cable satisfy the design requirements of a security cable for the transfer of data between computer terminals. The electric and magnetic shielding characteristics of the cables were researched in relationship to the security requirements. The magnetic shielding efficiencies of the four different materials were measured for possible use in the design of a magnetic shield with characteristics superior to thin-wall, steel conduit.

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SUMMARY

Data received from remote computer terminals transfer through several pairs of wires simultaneously. These cables need shields to block external electric and magnetic fields from the inner conductors and to block the radiation of internal signals for security reasons. The cable tested was an experimental design incorporating various manufacturing techniques. These techniques and materials were tested to develop a security cable for data transfer.

Electric fields in a frequency range from 1 to 200 kHz were tested for effective shielding. It was found that the shielding effectiveness of two finely braided shields plus an aluminum tape shield exceeded 145 dB. This measurement refers to a 12-inch (305 mm) section of cable and was well within the design requirements for a security cable.

Shielding tests on magnetic fields were conducted over a frequency range from 1 to 500 kHz. Magnetic shielding was not effective below 10 kHz. Above 10 kHz, layers of shielding produced increased magnetic shielding as a result of eddy current loss. These layers incorporated fine, braided wire and tape shielding.

Tests with twisted signal conductors were performed. Twisting the conductors proved to be effective in reducing external magnetic field pick-up; however, when an appropriate detector was tightly coupled to the signal conductors, very little attenuation of the radiating leakage was observed.

Additional magnetic shielding tests were conducted on various materials. These test samples included aluminum conduit, thin-wall steel conduit, iron water pipe, and a high permeability material 6 mil (0.152 mm) thick. The water pipe produced magnetic shielding in excess of 46 dB. This exceeded the thin-wall steel conduit by as much as 33 dB.

The high permeability shield was a double layer of spiral wound tape. Magnetic shielding characteristics equal to or superior to thin-wall conduit in the low-frequency region is believed possible with a cable of this nature.

Another area to be considered for maximum magnetic shielding effectiveness is a balanced system. This is a system that confines signal current flow to conductors within the shielding media. Magnetic shielding is not effective when a portion of the signal current returns to the source through another path (such as earth ground).

DISCUSSION

SCOPE AND PURPOSE

Present specifications for interconnecting computer stations require a secure system that uses a ferrous metal conduit. This conduit shields the information lines from the external environment. This approach, however, is limited in flexibility and would be expensive to install.

In an attempt to reduce installation cost and yet gain greater flexibility, an experimental cable was obtained by the Bendix Information and Equipment Security section of Department 531. The test or experimental cable incorporated various manufacturing techniques and materials (Figure 1). This project was initiated to determine the characteristics of the test cable and/or other materials to be used in an economical, flexible, security cable.

ACTIVITY

Compatible characteristics have been found in certain coaxial cables. These cables have an external homogeneous metal tube and a concentric inner wire. The test cable, however, has multi-layer shields which enclose six pairs of twisted wires. Because of the physical complexity, the individual shielding characteristics cannot be computed. The shielding characteristics were then referenced to known values as later defined in this report.

The test cable was 7/8-inch (22.2 mm) in diameter and approximately 40 feet (12.2 m) long. A specially designed terminal box 8 by 8 by 8 inches (203 by 203 by 203 mm) was totally enclosed and constructed of copper. It was attached to the source end of the test cable. All shields of the test cable were clamped to the terminal box (Figure 2) and six triaxial connectors were used to gain access to the six separate pairs of twisted conductors. Various layers of insulation and shielding material were removed from the terminating end of the test cable (Figure 3). This stair-step effect allowed the measurement of the over-all test cable performance and the effectiveness of each individual section.

Electric Field Effectiveness Evaluation

The test cable incorporated non-homogeneous metal shielding and was intended for use at a low frequency. The mechanism by which electric field leakage energy is transferred to and from the cable is referred to as transfer admittance. Simons¹ describes

NOTE: "A" THROUGH "F" ARE RADIAL DESIGNATORS

Figure 1. Experimental Cable Construction

Figure 2. Source End of Test Cable

NOTE: "A" THROUGH "F" ARE RADIAL DESIGNATORS

Figure 3. Terminating End of Test Cable

transfer admittance (Y) as the mutual capacitance (C) between the center conductor of a cable and the rest of the universe through openings in the shield.

$$Y = 2\pi fC$$

A voltage difference between the center conductor and a conductor outside the shield transfers energy per unit length (ΔX). This energy transfer is not affected by the current flow in the center conductor. Figure 4 illustrates the basic principle.

Figure 4. Basic Principle of Transfer Admittance

In the performance of the electric field leakage tests, a modified version of Figure 4 was used as shown in Figure 5.

The magnitude of V_1 is determined by the flow of leakage current (I_1) through the impedance of a spectrum analyzer (R). Equation 1 shows the shielding effectiveness in terms of both current and voltage per unit length ΔX .

$$\text{Shielding effectiveness (dB)} = 20 \log \frac{I_2 \cdot \Delta X}{I_1} = 20 \log \frac{V_2 \cdot \Delta X}{I_1} \quad (1)$$

where V_2 is the voltage drop across the 50 Ω termination and I_2 is the current through the 50 Ω termination.

Figure 5. Transfer Admittance Test Circuit

A technique commonly known as bulk cable testing was selected for electric field tests. In this technique, all inner conductors are connected, and the source voltage is applied between the inner conductors and shield. The six pairs of inner conductors of section B were treated as a single conductor with a common shield. A tightly coupled electric field sensor constructed of fine-braid copper wire was inserted over the test cable (Figure 6). By this arrangement, the sensor collected any leakage from transfer admittance.

Figure 6. Electric Field Sensor

The test frequency ranged from 1 to 200 kHz with test equipment (Figure 7). There was no detectable electric field leakage above system noise. Figure 8 is a plot of the greatest leakage curves. The leakage of a 12-inch (305 mm) and 48-inch (1.2 m) section of test cable were compared to the security cable design specifications. Because the electric field shielding of section B greatly exceeded the requirement of a security cable, no additional electric field tests were necessary.

Figure 7. Electric Field Test Circuit

Figure 8. Case of Greatest Electric Field Leakage:
Shielding Effectiveness Versus Frequency

Magnetic Field Effectiveness Evaluation

An analysis of the test cable construction provided some interesting conclusions. If the test cable were used at low frequencies (1 to 500 kHz), and if all signals entering a twisted pair of conductors returned through the same conductors, then the magnetic leakage field would totally result from the physical displacement of the two conductors. That is, the two conductors could not lie in the same physical location but would be displaced from each other (Figure 9).²

NOTE: DISTANCE "D" IS DEPENDENT ON
THE THICKNESS OF THE INSULATION

Figure 9. Conductor Pair Leakage Field

The leakage field vector rotates 360° as the conductors twist and spiral. The average leakage over one complete twist pitch, the length of one complete 360° spiral, approaches zero. This characteristic provides a very effective shield against external magnetic fields. Generally, the field is uniformly distributed along each twist length. The result is a pick-up average of zero.

For an effective magnetic shield, all of the current flowing into a pair of conductors must return to the source through the same pair.³ When a portion of the current returns by some other path (such as earth ground), there is an unbalanced current flow within the conductor pair. This results in a magnetic field which is not susceptible to the shielding around the conductor pair.

Several detectors were evaluated before taking magnetic field measurements. When the diameter of a pick-up coil detector was no larger than one-half of the twist pitch, the leakage from the currents within a twisted pair of conductors could be detected. When the detector was placed over the conductors (Figure 10) and positioned for maximum coupling, there was no apparent difference between twisted and straight conductors.

Figure 10. Magnetic Sensor Location

A magnetic field detector was selected for all subsequent magnetic leakage field measurements. Fifty turns of 5-mil (0.127 mm) coated transformer wire were wound on a 1/2-inch (12.7 mm) diameter fiber tube to make this detector. It had a coil height of 1/16 inch (0.159 mm). The output leads were twisted to provide shielding to external magnetic fields. Because the twist pitch of the test cable was 1 inch (25.4 mm), the effect of twisting the conductors was essentially removed from the measurement.

A twisted pair of conductors in the test cable are illustrated in Figure 11. This figure points out the reference field and areas of maximum leakage in the cable which will occur regardless of shielding. Test equipment is shown in Figure 12. A single pair of twisted conductors were selected from the test cable as the representative test sample. During testing, the positioning of the detector was as close to the points of maximum leakage as possible. Sections A through F were tested and the leakage information was read directly from the spectrum analyzer. The shielding effectiveness was recorded in terms of dB below the reference field. The effectiveness of magnetic shielding was compared to the security cable design specifications (Figure 13).

NOTE: THE LARGE SPIRAL IS A RESULT OF TWISTING SIX PAIRS OF CONDUCTORS

Figure 11. Test Conductor Pair Layout

Figure 12. Magnetic Field Test Circuit

Section A, insulated conductors without shielding, indicates that by locating the two conductors very close together, Curve A (Figure 13), the magnetic field leakage is reduced to 26 dB below the reference field. This was independent of frequency.

The preceding measurement data included the effects of detector distance from the twisted conductors. This made it very difficult to separate the individual shielding effectiveness of the test cable sections. The desired results were accomplished by normalizing the measurement data to a fixed radial detector location. Figure 14 is a plot of signal attenuation accompanied by an enlargement of the region of interest (Detail). The figure plots the distance from the conductors.

Figure 13. Magnetic Field Shielding Effectiveness Versus Frequency

Figure 14. Detector Signal Attenuation Versus Distance

The greatest distance from the twisted conductors, Section F, was selected as the normalized distance for the detectors. The distance and magnitude of normalized attenuation were tabulated for each section (Table 1).

Table 1. Normalized Attenuation

Test Cable Section	Detector Displacement	Normalized Attenuation
A to F	1/4 inch (6.35 mm)	-21 dB
B to F	15/64 inch (5.95 mm)	-20 dB
C to F	7/32 inch (5.56 mm)	-18 dB
D to F	5/32 inch (3.97 mm)	-13 dB
E to F	1/16 inch (1.59 mm)	-5 dB

Figure 15 presents the normalized information of Figure 13. This readily shows the desired shielding of each section of the test cable. Negligible shielding exists below 10 kHz, and only sections B and C provide shielding above 10 kHz as a result of eddy current loss.⁴ Section F, which contained the only ferrous material (rat guard), showed no magnetic shielding properties over the frequency range tested. The shielding effectiveness of Section A is a combined result of twisting the conductors, keeping the conductors physically close together, and sensing the field at a radial distance equal to Section F.

Because the test cable was found to have negligible magnetic shielding properties below 10 kHz, additional background information was desired, particularly the magnetic shielding properties of various solid materials. Four test samples were selected. The descriptions of the samples follow:

- Thin-wall steel conduit, 5/8-inch (15.9 mm) I.D., 13/16-inch (20.6 mm) O. D.;
- Aluminum conduit, 5/8-inch (15.9 mm) I. D., 23/64-inch (9.1 mm) O. D.;
- Iron Water Pipe, 5/8-inch (15.9 mm) I. D., 13/16-inch (20.6 mm) O. D.; and
- Double layer of spiral-wound tape, 6-mil (0.152 mm) thick, high-permeability metal.

Figure 15. Normalized Magnetic Shielding Effectiveness Versus Frequency

A leakage field that was normal to the paper was established as shown in Figure 16.

The detector was located at a fixed distance from the point of leakage. The location had to allow the test samples to be inserted over the field without affecting the detector position. Magnetic-shielding efficiency was measured by establishing a reference without shielding. The dB drop in signal level was then measured with the various test samples in place.

Figure 16. Reference Leakage Field

The results of the tests show that the water-pipe efficiency was beyond the capability of the measuring system (Figure 17) and that the nonferrous aluminum sample provided more shielding than expected.

In an attempt to use present manufacturing processes in the design of a cable shield, tests were made on a very crude hand-built, tape-wound shield. This high-permeability material, 6 mils (0.152 mm) thick and 3/8 inch (9.5 mm) wide, was wound in a double-overlapping spiral on a 5/8-inch (15.9 mm) O. D. fiber tube. Because longer material was unavailable, each tape strip was only 14 inches (356 mm) long. A very loose shield resulted.

Test data on the tape-wound shield indicated that it has a greater shielding efficiency than thin-wall conduit in the low-frequency region (Figure 17). The efficiency decreased as the frequencies increased. The shape of the curve suggests that most of the leakage is the direct result of the loose and crude construction of the shield.

The above results, though relatively inconclusive, suggest a possible design of a magnetic-shielding cable that uses high-permeability metals. Its characteristics would be compatible or superior to a thin-wall conduit at low frequencies. The possibility also exists that a properly designed soft-iron shield could provide adequate shielding to satisfy the security cable specifications.

Figure 17. Solid Shielding Efficiency Versus Frequency

ACCOMPLISHMENTS

Tests on an experimental cable and four types of magnetic-shielding materials yielded the following information.

- The effectiveness of electric-field shielding of two braids and an aluminum-tape shield exceeded the design requirements of a security cable by 65 dB.

- Increased magnetic shielding was obtained by twisting the conductors and placing them close together.
- Nonferrous shielding exhibited some magnetic-shielding properties above 10 kHz.
- The spiral shield of iron tape (rat guard) did not exhibit any magnetic-shielding properties over the frequency range from 1 to 500 kHz.
- Tests were made on the magnetic shielding of a thin-wall steel conduit and a spiral-wound shield of high-permeability material. These tests could help develop specifications to construct a flexible cable shield with magnetic-shielding characteristics equal to or superior to the thin-wall conduit at frequencies below 10 kHz.
- A magnetic-field detector capable of detecting the leakage from a twisted pair of conductors was developed.
- It was found that a balanced system that confines the current flow within the shield is essential to effective magnetic shielding.

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