This month we continue our series on wire. Having previously discussed shielded wire in general, capacitive and inductive coupling, shielding methods and the characteristics of coaxial cables, we will now study in detail what occurs inside a coaxial cable between the center conductor and shield when a high frequency signal travels from source to load. The reference for this series of articles is the FAA's Advisory Circular AC 43.13-1B *Acceptable Methods, Techniques and Practices for Aircraft Inspection and Repair.* The document is readily available at www.faa.gov/avr/afs/300/pdf/1a-cover.pdf.

Last month we discussed the importance of not damaging coaxial cables by subjecting them to any type of abuse that can cause the characteristic impedance to change from its desired value (typically 50 ohms). The reason for this is because the higher frequency signals do not flow through the cable in the same way as lower frequency signals and direct current. This is due to the *skin effect*. *The skin effect is the tendency of a high-frequency signal current to distribute itself in a conductor so that the current density near the surface of the conductor is greater than that at its core*. It causes the effective resistance of the conductor to increase with the frequency of the current. What follows may be difficult to understand, but if you are willing to roll up your sleeves and work through it, the comprehension gained of this esoteric phenomenon will pay dividends when following published installation procedures and troubleshooting problems involving high frequency signals. For the remainder of this article, reference Figure 1 below.

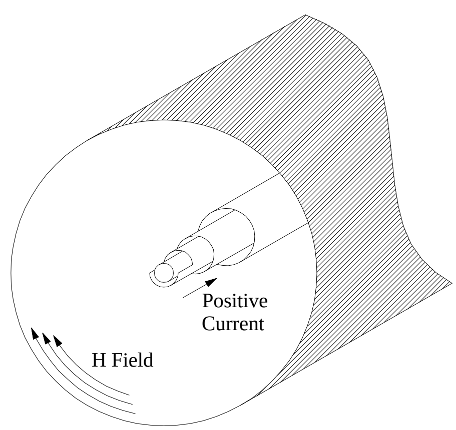

Figure 1 Coaxial cable cut-away showing skin effect.

For any signal traveling down a conductor, the current density, **J**, decreases exponentially with depth, **D**, as follows:

$$J = e^{-D/d}$$

where **e** is the natural logarithm (about 2.72). **e** has many remarkable properties similar to **p** in that it is a fundamental constant of nature, and is an irrational number- that is, **e** is not the root of any polynomial equation with rational coefficients, or simply "the numbers to the right of the decimal point just keep going and going on forever without ever repeating". Just as we live in a dimension of time, how we live is in many ways determined by the nature of **e**.

where **d** is a constant called the skin depth. The skin depth is defined as the depth below the surface of the conductor at which the current has decreased by 63.2% or 1/**e**. This is where the AC resistance of a conductor is measured. The skin depth is dependent upon the frequency of the current.

Getting beyond the math, the equation is interpreted as follows: Looking at a conductor at its surface, the depth D is zero, therefore D/d is zero and any value raised to the power of zero (in this case **e**) is one. Therefore the current density is at maximum. Looking at a conductor at its skin depth d, the equation reduces to $J= e^{-1}$ or 1/e, which is our definition of skin depth above. Looking at a conductor at depths below the skin depth, the current density of the conductor reduces as $1 / \mathbf{e}^{\,n}$, where n is some positive number greater than 1.

The skin depth, d, is determined by the following formula:

$$d = (2 \rho / \omega \mu)^{1/2}$$

where r is the resistivity of the conductor, w is the angular frequency of the current or 2 p x frequency, and m is the magnetic permeability of the conductor. This formula can be reduced for typical 50 ohm coaxial cables found in our industry with copper wire to:

$$d = 2.602 / (f_{HZ})^{1/2}$$

where **d** is the skin depth in inches, and $\mathbf{f}_{HZ}$ is the current frequency in Hertz.

Looking at real world examples we can assume that DC current flows evenly throughout a conductor, utilizing all available copper. Below is a table of skin depths verses frequency.

Frequency	Skin Depth	Frequency	Skin Depth
DC	depth of conductor	100 Mhz	0.00026”
10 Khz	0.026”	330 Mhz	0.00014”
100 Khz	0.008”	1 Ghz	0.000082”
1 Mhz	0.003”	4.3 Ghz	0.000040”
10 Mhz	0.0008”	9.375 Ghz	0.000029”

To put these values into perspective, consider that the thinnest plastic wrap that you can buy (i.e. for covering dishes or food) is approximately 0.001” or 1 mil thick. Your GPS, Transponder and DME coaxial cables are utilizing only 82 *millionths of an inch* of surface copper for the majority of their current flow. Now you can see how physical damage to coaxial cables of any type can affect their performance.

For those interested in a rigorous mathematical explanation of skin effect, see references below.

This concludes the series on wire. Hopefully these articles have shed light on the attributes of wire and how better to install avionics and maintain our industry’s aircraft.

References

1. Dr. Johnson, Howard, “Modeling Skin Effect”, April 12,2001, Electronic Design News (EDN), P26.
2. Carr, Joseph J., “Comm Links- RF Shielding”, August, 1999, Popular Electronics, P82.

Next Month: Aircraft Maintenance Entries