Precision Video Coaxial Cables
Part 1: Impedance

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Abstract: *Over the years, engineers have come to identify coaxial cables typically in one of two ways: either by impedance or RG-type. The impedance refers to the characteristic or nominal impedance of the cable. Recently, some manufactures have begun to specify tighter requirements on the cable. This paper will examine the nature of characteristic impedance and to what extent the values are relevant.*

Characteristic Impedance: A signal travels, or propagates, through a transmission line. Therefore, its behavior is defined by the propagation constant.

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (1)$$

Where:
- γ is the propagation constant
- α is the attenuation constant
- β is the phase constant
- R is the resistance
- L is the inductance
- G is the conductance
- C is the capacitance
- f = frequency in Hertz
- $\omega = 2\pi f$ = radian frequency

The signal can be described in many ways to better understand its properties and behavior. The natural approach is to divide the signal into voltage and current. By knowing the properties of the dielectric material in the transmission line, we can then determine the intrinsic impedance. Thus, a positively traveling current wave is related to a positively traveling voltage wave by the intrinsic impedance

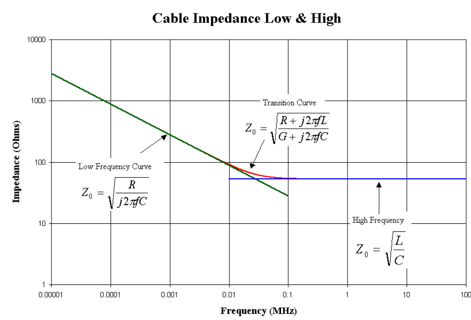
$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \quad (2)$$

Where:
- η is the intrinsic impedance
- μ is the permeability
- σ is the conductivity
- ε is the permittivity

The intrinsic impedance is analogous to the characteristic impedance, Z_0. Characteristic impedance is a more common term made up of values we often see associated with coaxial cable: Resistance, Inductance, Capacitance, and the lesser known Conductance.

$$Z_0 = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}} \quad (3)$$

Solving the characteristic impedance formula results in the curve and simplification formulas shown below.



GRAPH 1

At high frequencies, typically greater than 1 MHz, the coaxial cable will approach the "steady state" value that is referred to as the nominal or typical impedance. This is the value stated by most manufacturers as the characteristic impedance.

Therefore the common expression used to identify the characteristic impedance of a coax is:

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\frac{D}{d} \quad (4)$$

and is also simplified to:

$$Z_0 = \frac{101670}{C * Vp} = 138\frac{Vp}{100}\log\left(\frac{D}{d}\right) \quad (5)$$

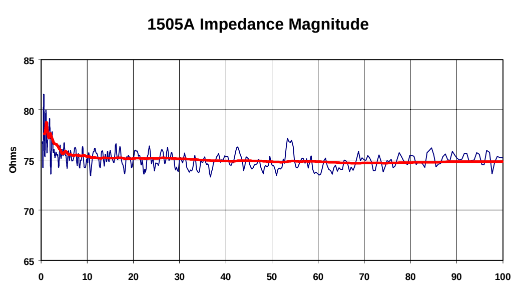
Where: D is the diameter over the insulation
d is the diameter of the conductor
C is the Capacitance (pF/ft)
Vp is the Velocity of Propagation (%)

All of these formulas will provide a good approximation of the high frequency characteristic impedance of a coaxial cable.

Traditionally, cable manufacturers have specified this value as typical or nominal. In some cases, the value had a tolerance. In the case of video cable, a typical value was 75 ± 3 ohms. Therefore, the characteristic value is between the value of 72 and 78 ohms or about ± 4%. Some precision video cables, such as Belden 8281, made with a solid conductor and solid polyethylene dielectric were specified as ± 1.5 ohms, or ± 2%.

Recently, manufacturers have begun to tighten this impedance tolerance. This is due mainly to the use of statistical process control and the infiltration of automation into the manufacturing process. These improvements allow the cable manufacture to more consistently meet the 75 ohm target. While some manufactures try to use this specification as a selling point or technical advantage, it must be remembered that this is the nominal impedance of the cable and does not account for the true impedance variations within the cable.

The graph below illustrates this point. This is an impedance trace of Belden 1505A Precision Video Cable. Notice how the impedance follows the theoretical characteristic impedance (red line), but that the actual impedance does have variation (blue line).



GRAPH 2

Belden 1505A is specified as 75 ± 1.5 ohms and does meet the requirement as shown in this graph. It is also obvious that the impedance at individual frequencies is not within the characteristic value tolerance. So, what then is the value of a tight characteristic impedance tolerance?

Input Impedance: Input impedance is the term used to describe the impedance at any given specific frequency. The term vector impedance is also sometimes used.

Unfortunately, this impedance is not uniform at all locations and all frequencies within the cable. After all, this is the REAL world! Therefore, what is really happening within a cable can be best understood (and measured) by looking at the reflection coefficient.

When signal traveling in a coax encounters an impedance mismatch, a portion of the signal will be reflected back to the source. This reflected signal has magnitude and phase and is measured as the reflection coefficient.

$$\Gamma = |\Gamma| e^{j\phi} = \frac{Z_{02} - Z_{01}}{Z_{02} + Z_{01}} \quad (6)$$

Where: Γ is the reflection coefficient
ϕ is the phase angle

By measuring these signal reflections we can determine what is happening within the coax. We can calculate the actual mismatches.

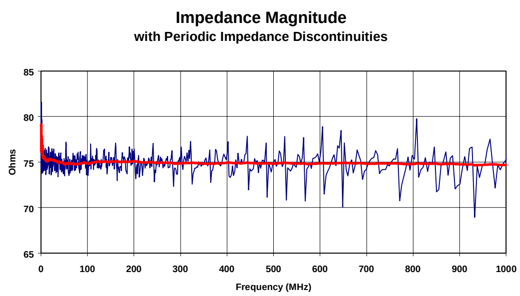
We can also look at the input impedance with respect to frequency and length using the reflection coefficient. This formula is written in terms of the impedance variation within the transmission line.

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l} \quad (7)$$

Where: Z_{in} is the input impedance
Z_0 is the characteristic (or reference) impedance
Z_L is the load impedance at a specific location
$\tan \beta$ is the tangent of the phase angle
l is length

The input impedance, Z_{in}, is represented in the GRAPH 2 as the blue line. Z_{in} represents specific impedance at specific lengths. Length equates to wavelength equates to frequency. Therefore, impedance variation at specific frequencies can be measured. This will more accurately predict the electrical performance of the cable.

An extreme example of this can be shown with a cable that has an excellent characteristic impedance value (red line), but has terrible impedance variation within the cable (blue line). This cable, too, meets the same requirement as the previous example, 75 ± 1.5 ohms.



GRAPH 3

The characteristic impedance value is important because the cable must be as close to 75 ohms as possible to minimize reflective losses. But it is more critical that the variation of impedance around the nominal be minimal. This is why impedance is important. Impedance mismatches cause signal reflections.

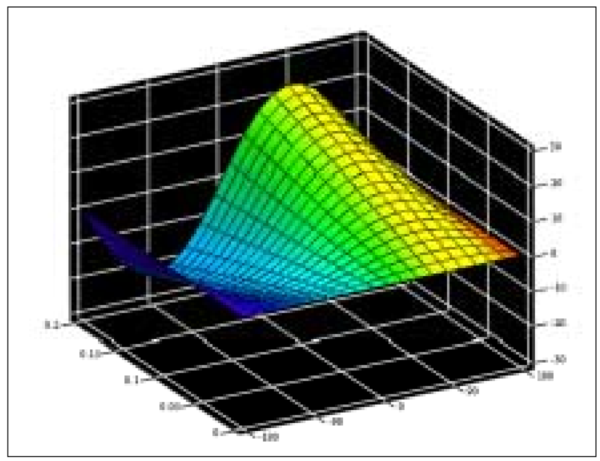
So, again the question, what then is the value of a tight characteristic impedance tolerance? It would seem that the characteristic impedance value alone will not guarantee the performance level of the cable. Rather it is primarily a specmanship issue.

Note also that the characteristic impedance value is a *magnitude* only measurement, while the reflection coefficient and input impedance measurements both include *phase*.

Why Magnitude Only: Because of the high frequency characteristic impedance properties, a magnitude only measurement allows for simplified calculations and measurements to be used to represent the relative characteristics of the cable. These include TDR (Time Domain Reflectometer) impedance, calculated per MIL-C-17G, and calculated per the simplified formulas.

Also, a closer look at the input impedance equation (7), will show that the phase angle should be near zero in a “good” cable. This is because when you divide a complex number, you actually subtract it. Assuming that the angle is about the same in both parts of the equation, the end result should be a phase angle about zero degrees.

Using our equations for reflection coefficient (6) and input impedance (7), lets look at the impedance phase with the assumption that the cable has reasonably low impedance variation. These assumptions reveal that the impedance phase will be less than ± 20 degrees as can be seen in GRAPH 4.



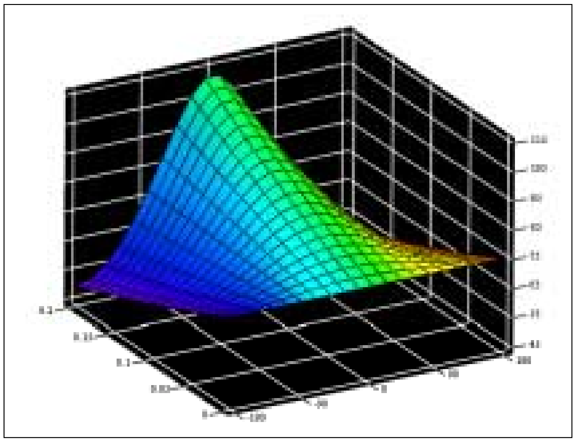
GRAPH 4

x: Reflection Coefficient Phase
y: Reflection Coefficient Magnitude
z: Impedance Phase
Reflection coefficient for reference
.20 = 14db RL = 1.5:1 VSWR
.15 = 16.5db RL = 1.35:1 VSWR
.10 = 20db RL = 1.22:1 VSWR
.05 = 26db RL = 1.11:1 VSWR
.00 = infinite RL = 1.0:1 VSWR

Here we can see that as the reflection magnitude nears zero, so does the impedance phase. Also, the larger the reflection coefficient magnitude, the more effect the reflection coefficient phase has on the impedance phase. So, to minimize impedance phase, the reflection coefficient must be minimized. This means there must be minimal impedance variation within the cable.

The input impedance formula does not “limit” the variation or value of the impedance magnitude the same way it does the phase. Therefore, we can have a much wider variation of impedance magnitude as a result. Using the same assumptions, the impedance magnitude can vary ± 30 ohms as can be seen in GRAPH 5.

Here we see as the reflection coefficient magnitude approaches zero, the impedance magnitude approaches its characteristic value of 75 ohms. Also, the lower reflection coefficient magnitude, the less effect reflection coefficient phase has on the impedance.



GRAPH 5

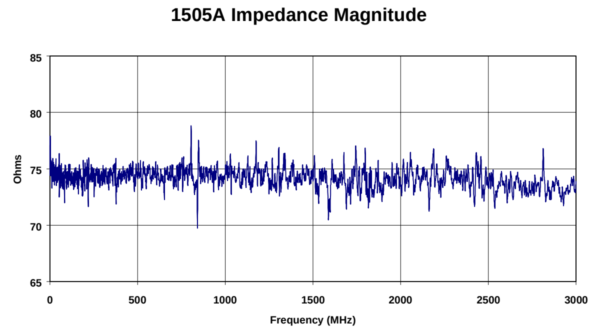
x: Reflection Coefficient Phase
y: Reflection Coefficient Magnitude
z: Impedance Magnitude

Minimizing the reflection coefficient magnitude is the key. Here we truly see that a minimum reflection coefficient magnitude means that the cable should be very near its characteristic impedance.

So, a perfect cable with minute impedance variations will have minimal reflection coefficient and will be at its characteristic impedance value. However, a cable with excellent characteristic impedance can still have impedance variance of ± 30 ohms. So, again the question, what then is the value of a tight characteristic impedance tolerance?

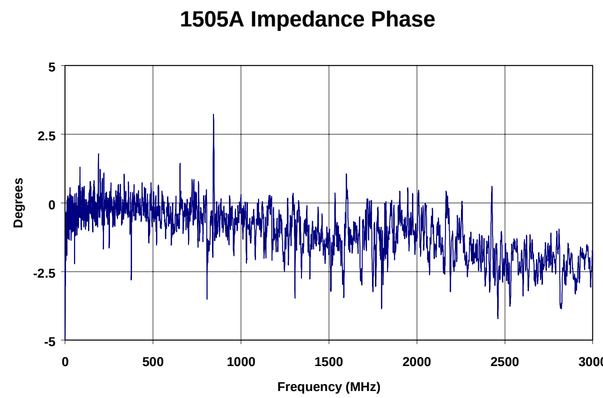
Actual Cable Measurements: If we apply this theory and put it together with frequency, what will the values be?

This data is measured from 300 kHz to 3.0 GHz using a network analyzer from a randomly chosen spool of Belden 1505A. The sample length is 100 feet.



GRAPH 7

Notice that the impedance grass is about +/- 3 ohms and that the characteristic impedance is about 74.8 ohms.



GRAPH 8

Notice that as we predicted, the impedance phase angle is near zero.

Note: This data was collected using a 2.5GHz S-parameter test set. Actual values above 2.5 GHz may not be correct.

As we can see from the actual data, our theory holds true. The impedance magnitude is centered around the characteristic value and the phase is near zero. This explains why manufactures report the characteristic impedance magnitude only. It further shows that the actual tolerance of the impedance at any given frequency will be greater than the characteristic impedance tolerance value. (The tolerance is the “grass” around the best-fit-line value.)

Magnitude and Phase Together: Since both impedance magnitude and phase can be affected within the cable, it makes sense to look at both to determine the true performance of the cable. What measurement and specification will do this best? This will be discussed in more detail in Part 2 of our technical series.

Specmanship: So, how tight can the characteristic value be held? Given excellent manufacturing practices, materials, product designs, SPC implementation, measurement and operator capabilities, the standard deviation for characteristic impedance will be 0.5 ohms or less.

Belden uses a 6-sigma approach when setting specifications to guarantee the customer that our products will meet or exceed expectations. In statistical terms, this means that the CpK is greater than 1.33 or that more than 99.9934% of product falls within the specification limits.

Thus for characteristic impedance, we specify +/- 3 standard deviations which will be:

$$\pm 3\sigma = \pm 3 * 0.5 = \pm 1.5 Ohms$$

Belden's tolerance for characteristic impedance for precision video cables is 75 +/- 1.5 Ohms. (Belden products 8281, 1855A, 1505A, 1694A, 7731A, and others.)

Given our historical test lab data on this cable, most cable is within 75 +/- 0.75 ohms. This will be further illustrated in Part 2.

Conclusion: Characteristic impedance is not a true representation of the performance and/or quality of a transmission line. This was best illustrated in GRAPH 3. This cable has had a periodic discontinuity introduced into the cable. (A slight compression at 10 foot intervals.) Notice that the input impedance shows the defect, but characteristic impedance does not. A TDR measurement may show some of the defects, depending on how far into the cable you look, but the resultant value may not.

Therefore, the characteristic impedance value alone – or it's tolerance – does not tell the whole story of cable quality or performance. A specification for impedance variation, both magnitude and phase, is required to demonstrate this capability. This will be the topic of part two in this series.

Part 2: In our next paper, the use of the reflection coefficient will be discussed, using the measurements of Return Loss, Voltage Standing Wave Ratio, and Structural Return Loss to guarantee cable performance and minimize impedance variations within the cable.

About the Author:

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Marty is a Senior Product Engineering Project Manager for Belden Electronics Division. His experience encompasses project management and product development positions. He currently has responsibility for all design and development efforts, and manages the day-to-day activity of product engineers, for Belden's entertainment, service provider, and industrial product areas. Marty received his Bachelor of Science Degree in Electrical Engineering (BSEE) from Marquette University, Milwaukee, WI in 1992 and has been with Belden since that time. He is a member of several professional organizations and standards bodies, and has had several articles on Audio/Video and RF topics published in trade magazines: most recently, a co-authored tutorial on "High-Definition Cabling and Return Loss" in the January 2001 SMPTE Journal. Marty also holds a FCC Amateur Extra Class amateur radio license. He and his wife Beth live in Richmond, IN.

Marty Van Der Burgt

Graphs and data formatted by Carl W. Dole.