Coaxial Cable Insertion Phase Measurement and Analysis

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Abstract

Insertion phase of coaxial cable under conditions of temperature change and flexure will be examined. Its definition, significance, IEC standards, measurement methods, and data analysis methods will be discussed.

Introduction

The insertion phase of coaxial cable is important to wireless and other markets that use coaxial cable in radio frequency (RF) applications. These cables may transport signals that require predictable insertion phase characteristics for the system to function properly. For example, an antenna array where the driven elements are interconnected with coaxial cables will be subject to the temperature extremes of an outdoor environment. These temperature variations will change the insertion phase of the coaxial cables, which could significantly change the antenna radiation pattern due to the alteration of the phasing of the signals applied to the antenna elements. Cables within equipment assemblies may provide important phasing between modules, which could change as the temperature in the equipment changes.

Equipment that involves flexure of coaxial cables may be adversely affected by insertion phase changes in the cable. For example, robotic equipment or moveable antenna arrays would have flexure as a concern. This could adversely impact the equipment performance to the extent that it would no longer conform to its published specifications.

Unfortunately phase characteristics of coaxial cable are sometimes not given, or if they are given, are very brief. What is missing is an explanation of how it was determined, what conditions it was measured under, or how to apply it to system design. This paper will explain what insertion phase is, how it is measured and evaluated, and how to apply the results to system design.

Definition

Insertion phase is the phase change that occurs to a signal as it propagates through a transmission line. Coaxial cable serves as the transmission line for many RF signals. Insertion phase can also be thought of as the time it takes for a signal to pass from one end of the cable to the other. Phase is expressed in radians or degrees, and time is expressed in seconds. Because RF signals travel so fast, time is usually expressed with smaller units such as milliseconds, microseconds, or nanoseconds. Phase is related to time if the velocity though the cable and the frequency of the signal are known.
Take for example the propagation of a signal through the cable of Figure 1. A signal is injected into end A of the cable at time $t_0$ and exits the cable at end B at time $t_1$. The velocity ($v_c$) and length ($l$) determine the time it takes the signal to travel from end A to end B.

![Figure 1 – Signal Propagation Time Through a Cable](image)

Mathematically, the difference between $t_1$ and $t_0$ is:

$$t_1 - t_0 = \frac{l}{0.01c v_c}$$

(1)

Where: $t_0$ = Time signal enters cable at end A (seconds)  
$t_1$ = Time signal exits cable at end B (seconds)  
$c$ = Velocity of light in vacuum (3 x $10^8$ meters/second)  
$l$ = Length of cable (meters)  
$v_c$ = Velocity of propagation in cable (percentage of $c$)

If $t_0$ in Equation (1) is set equal to zero, $t_1$ is the time ($t$) it takes the signal to travel through the cable, and the equation simplifies to:

$$t = \frac{l}{0.01c v_c}$$

(2)

Where: $t$ = Time for signal to pass through cable (seconds)

The velocity of propagation ($v_c$) in the cable is normally expressed as a percentage of the velocity of light in a vacuum ($c$), hence its inclusion in equations 1 and 2. The velocity of light is the “speed limit” for electrical signals and is never reached in coaxial cable. Velocities range from 66 percent to 86 percent for typical flexible coaxial cables (Table I). For a given length of cable, the velocity of the cable determines the time $t$ for the cable. The type of dielectric material, the material between the center and outer conductors, determines the dielectric constant, which is the primary determinant of the velocity of the cable. Dielectric constant, or relative permittivity ($\varepsilon_r$), is related to velocity.
\[ v_c = \frac{100}{\sqrt{\varepsilon_r}} \]  \hspace{1cm} (5)

Where: \( \varepsilon_r \) = Relative permittivity or dielectric constant

<table>
<thead>
<tr>
<th>Dielectric Material</th>
<th>Dielectric Constant</th>
<th>Velocity of Propagation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene (PE)</td>
<td>2.3</td>
<td>66</td>
</tr>
<tr>
<td>Tetrafluoroethylene (TFE)</td>
<td>2.07</td>
<td>69.5</td>
</tr>
<tr>
<td>Foamed Polyethylene</td>
<td>( \geq 1.35^* )</td>
<td>( \leq 86^* )</td>
</tr>
<tr>
<td>Air</td>
<td>1.02 (approximately)</td>
<td>99 (approximately)</td>
</tr>
</tbody>
</table>

* Depends on amount of foaming.

Dielectrics that are foamed contain a mixture of solid material and air or a gas such as nitrogen. The addition of air or gas raises the velocity above that of the unfoamed compound. The resulting velocity depends on the degree of foaming, which is controlled during the manufacturing process.

Figure 2 – Parallel Signal Paths with Insertion Phase
Significance

Take the example where two cables of equal physical length have different insertion phase because of the velocity difference (Figure 2). The signals exit the cables at different times ($t_1$ and $t_2$) even though they enter at the same time ($t_0$). If signals A and B are required to arrive at the output end of each cable simultaneously, the difference could adversely effect the operation of the system.

International Standard

IEC 60966-1 [1] provides an international standard to use in evaluating phase variation. For temperature (8.8 Phase variation with temperature) the standard specifies a minimum loop diameter of at least ten times the minimum static bend radius, six temperature cycles, and a network analyzer to perform the measurements. The only mention of how to present the data is a suggestion of °el/°C (i.e. degrees of electrical length change per degree Celsius of temperature change) with no explanation. Also, the sample length is not specified.

For flexure (8.6 Stability of electrical length) the standard provides figures of the test sample positions using a mandrel to control the bending and twisting. The dynamic bending radius of the cable is suggested as the mandrel radius. The number of bending and twisting cycles is not specified. A network analyzer is used for the measurements. Again, the sample length is not specified.

Cable assemblies (i.e. cables with connectors installed) are specified for both temperature and flexure testing. This implies the use of permanently installed connectors. Also, the standard implies the entire cable assembly should be placed in the temperature chamber. An alternative is to have portions of each end of the sample outside of the chamber for connection to the equipment with the data analysis taking this into account.

Equipment Setup and Measurement

Insertion phase of a cable is typical determined by inserting a signal into one end of the cable and measuring the time the signal exits the other end of the cable, relative to the input time. A network analyzer would typically be used for this measurement. First the network analyzer is set up for the frequency range of testing, number of data points for the frequency span, sweep time, and IF bandwidth.

The analyzer is set for a through measurement of phase ($S_{21}$, Phase) and normalized with a through connection from the output port to the measurement port (Figure 3). The cable under test (CUT) is then inserted into the through path (Figure 4). Note that the cable used for normalization is included with the cable under test. Without this cable, the CUT will not be accurately measured.
Several precautions must be heeded when setting the analyzer. First, a sweep time that is too short (i.e. fast sweep) can cause erroneous measurements. The receiver of the network analyzer tunes its frequency to match the frequency of its output signal. A fast sweep can result in the receiver being tuned to a frequency different than the frequency of the signal coming out of the cable. This is because of the time it takes for the signal to travel through the cable.

The easiest way to determine if the sweep time is too fast is to increase it and watch the insertion loss display ($S_{21}$, log magnitude) on the analyzer. If the amplitude of any portion of the display changes, the previous sweep time was too fast. Continue increasing the sweep time until the amplitude no longer changes. It is advisable to monitor the insertion loss and insertion phase simultaneously using a dual network analyzer display. Measurement problems such as bad connections or excessive insertion loss can easily be seen this way.
Secondly, the intermediate frequency (IF) bandwidth setting of the network analyzer is related to the sweep time. Think of it as the size of the receiver window. The wider the window is, the less critical is the need to center the received signal in this bandwidth. Consequently, the wider the bandwidth, the faster the allowable sweep time. A disadvantage of a wider bandwidth is a higher receiver noise floor, which reduces the dynamic range of the analyzer. This can be a problem with long cables where the insertion loss approaches the noise floor at the highest frequencies of the sweep.

Third, the number of data points can be too small for a given frequency span and cable length to give an accurate phase measurements. The issue is how much phase change occurs between adjacent measurement frequencies (equation 6). If it exceeds 180 degrees the data can be difficult to properly interpret. Increasing the number of data points, decreasing the frequency span, or decreasing the cable length can correct the situation. The first two remedies decrease the frequency step between adjacent frequencies, whereas the last does not.

\[ \Delta \phi_{\text{Step}} = 3.6 \times 10^4 \left[ \frac{f_{\text{stop}} - f_{\text{start}}}{\text{NOP} - 1} \right] \frac{l}{c v_c} \]  

Where:
- \( \Delta \phi_{\text{Step}} \) = Phase change between adjacent data points (degrees)
- \( f_{\text{stop}} \) = Stop frequency of sweep (Hz)
- \( f_{\text{start}} \) = Start frequency of sweep (Hz)
- NOP = Number of data points per sweep

Adjusting the analyzer’s electrical delay control is another way to overcome the problem of excessive phase change between data points. This control mathematically adjusts the analyzer’s phase reference to that the trace can become nearly horizontal. It must be remembered that the displayed trace is not the absolute total phase of the cable. This may be acceptable if only changes in phase are of interest, such as with temperature of flexure. The total phase can be calculated as explained in the following section.

Finally, the cable must be short enough that the signal out of the cable is above the noise floor of the analyzer receiver. Monitoring the insertion loss, as mentioned earlier, will indicate whether this requirement is met. However, if the cable is very short, the total phase of the cable will be small and phase measurement errors could become a large percentage of the measurement.

**Network Analyzer Phase Interpretation**

The typical network analyzers only have a 360-degree range (±180 degrees) of phase measurement. When the insertion phase exceeds this range the display makes an abrupt 360-degree transition, resulting in a sawtooth pattern with many transitions possible (Figure 5). For example a phase of 200 degrees would be displayed as –160 degrees (200 degrees – 360 degrees) or -200 degrees would be displayed as +160 degrees (-200 degrees + 360 degrees).
Since the time delay through a cable is nearly constant with frequency, the resulting display has a nearly symmetrical sawtooth pattern from the multiple 360-degree transitions. These transitions can be removed by Equation (7) to obtain the total phase of the cable (Figure 5) [2].

$$\phi_{total} = \phi_{na} + k \times 360$$  \hspace{1cm} (7)

Where:
- $\phi_{total}$ = Total insertion phase (degrees)
- $\phi_{na}$ = Insertion phase from network analyzer (degrees)
- $k$ = Integer number of 360 degree phase transitions (e.g. 0, 1, 2, etc.)

The initial value of integer $k$ at the start of the frequency sweep must be determined. The total expected phase ($\phi$) is calculated with Equation (8) and $k$ is adjusted in integer increments so that $\phi_{total}$ is as close as possible to $\phi$. As frequency increases across the sweep, the $k$ value is then incremented by one at each transition if the slope prior to the transition is positive. It will be decremented for a negative slope.

$$\phi = 3.6 \times 10^4 \frac{f l}{c v_c}$$  \hspace{1cm} (8)

Where: $\phi$ = Insertion phase (degrees)

**Phase Change Analysis**

Insertion phase change is often of interest in system design. The initial total insertion phase is used as a baseline phase reference for calculating phase change. It is subtracted from subsequent measurements to obtain the phase change at each frequency of the sweep (Equation (9)).

$$\Delta \phi = \phi_{total} - \phi_{ref}$$  \hspace{1cm} (9)

Where:
- $\Delta \phi$ = Insertion phase change from reference (degrees)
- $\phi_{ref}$ = Initial reference insertion phase (degrees)
The phase change versus frequency has a nearly constant slope, which allows for a simplified expression of the phase change by relating it to frequency and length (Equation (10)). This calculation has a nearly constant value across the frequency span (Figure 6). It is similar to group delay which is the derivative of phase with respect to frequency. The advantage of \( \text{elect deg/GHz/m} \) is that a single number can define the phase change limit across an entire frequency range. This can be used to calculate phase change for any frequency and length.

\[
\text{elect deg/GHz/m} = \frac{\Delta \phi}{f l}
\]  

(10)

Where: \( \text{elect deg/GHz/m} \) = Electrical degrees/GHz/meter

\( f \) = Signal repetition frequency (GHz)

![Figure 6 – Phase Change Example](image)

Parts per million \((\text{ppm})\) is another way to express the phase change (Equation (11)). This calculation also results in a nearly constant value across a frequency span.

\[
\text{ppm} = \frac{\Delta \phi * 10^6}{\phi_{AbsRef}}
\]  

(11)

Where: \( \text{ppm} \) = Parts per million insertion phase change (degrees)

\( \phi_{AbsRef} \) = Absolute total reference insertion phase (degrees)

It should be noted that \( \phi_{AbsRef} \) is the absolute total insertion phase of the cable without the effect of the network analyzer electrical delay setting (Equation (12)).

\[
\phi_{AbsRef} = \phi_{total} - 360 f \ Delay_{na}
\]  

(12)

Where: \( Delay_{na} \) = Delay setting of network analyzer (seconds)
Conclusion

The insertion phase of flexible coaxial cable can be changed by temperature and/or flexure. Quantification of this change can be important for proper operation of a system. IEC standard 60966-1 provides an internationally recognized test method to use in evaluating coaxial cable when subjected to temperature changes and/or flexure. This paper has presented methodology for measuring insertion phase and analyzing the resulting data in an attempt to “fill in the gaps” contained in the IEC standard. This methodology is used on Belden coaxial products that contain phase change specifications.

References


Links

“Temperature and Flexing Effects on Coaxial Cable Insertion Phase, Insertion Loss, and VSWR”

NP182 Belden® Expands Line of Low Loss 50 Ohm RF Transmission Cable
NP157 Belden® Introduces New Low Loss 50 Ohm RF Transmission Cable
NP106 Belden® Introduces Conformable® Coax Cable for Microwave and High Frequency Video Applications.

Biographical Notes

Carl Dole is a Product Engineer and has been with the Belden Engineering Center of Belden Electronics Division for nearly thirteen years. He currently holds one U.S. patent. He has authored and co-authored numerous technical papers. His academic achievements include a B.S. degree in Electrical Engineering Technology (“With Highest Distinction”) from Purdue University. Prior to joining Belden, Carl worked 10 years in television broadcast engineering, is a Certified Senior Broadcast Engineer, and has a lifetime FCC General Class Radiotelephone License. His areas of responsibility include developing improved electrical test methodologies, writing technical papers, and working on new product development teams. He is a member of SMPTE, IEEE, and SBE.