AMSE JOURNALS-AMSE IIETA publication-2017-Series: Advances B; Vol. 60; N°2; pp 389-400
Submitted Mar. 07, 2017; Revised May 11, 2017; Accepted May 31, 2017

Analysis of Signal Transmission Performance of Radio Frequency Cable under Multiple Factors

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Abstract

The performance of radio frequency (RF) cable, the main physical carrier of signal transmission, is affected by multiple factors. This paper sets up a 3D finite-element model of the RF cable to study the signal attenuation features of such single factors as insulating layer thickness, signal frequency and ambient temperature. Then, the insertion loss and variance analysis of nine parameters of the RF cable were discussed in orthogonal design. The results show that the signal attenuation is positively correlated with signal frequency and ambient temperature, but negatively correlated with the insulating layer thickness; in terms of the effect on insertion loss, the parameters are ranked as signal frequency>insulating layer thickness>ambient temperature in descending order. Next, the author obtained the signal features and proposed a multivariate regression model. The experimental results show that the model has an error of less than 3%, an evidence of high accuracy.

Key words

Radio Frequency (RF) cable, Signal attenuation, Orthogonal design, Regression model.

1. Introduction

As the bridge between transmitters and receivers, the radio frequency (RF) cable has been extensively applied in communication, broadcasting and electronic equipment. The performance of the cable has been gradually improving with the development of its design and manufacturing techniques. Despite the gradual improvement, the signal transmission performance of the RF cable is being affected by the increasingly intensive communications in the modern era and growing signal frequency of electronic equipment. Amidst such disturbances, it is critical to maintain the accurate transmission of key signals in the cable.

Concerning the signal transmission performance of the RF cable, most of the existing studies are in the form of single variable analysis. By contrast, multi-variable analysis on the topic is rarely seen. Some scholars probed into the effect of temperature and signal frequency on the performance, but failed to measure the combined effects of temperature, frequency and structure. Other studies on the RF cable are summarized as follows. References [1-2] calculate the transient and coupling voltages of the RF cable; Reference [3] proposes a simplified method to calculate the voltage attenuation of the cable; Reference [4] studies the signal amplitude and phase of the RF cable at different temperatures; References [5, 6] analyses the response of high-frequency signals to interconnected terminals; Reference [7] studies the signal integrity by the Finite Difference Time Domain (FDTD) method and the finite-element method; References [8-9] employs the finite-element method to examine the multi-physics problems in power generators; Reference [10] explores the attenuation factors of the RF coaxial cable; Reference [11] obtains insulating layer thickness and other main structural factors of signal attenuation, and relies on these factors to analyse the attenuation of RF photonic signals; Reference [12] discloses the performance features of the RF cable, and verifies the S-parameters of the linear coupling model in experiments. The high-frequency and high-temperature environment exerts a major effect on the transmission of different kinds of RF cable signals, especially the accuracy and completeness of the signals. Targeted at the RF coaxial cable, Reference [13] establishes a finite-element model to analyse the ambient temperature and signal frequency.

In view of the above, this paper constructs a regression model of the RF cable to study the signal attenuation features of multiple factors, and obtains the effect of these factors on the signal transmission performance of the RF cable through experimental verification and correction.

2. Basic Theory of S-Parameters

In the RF cable, an electromagnetic field is formed between the inner and outer conductors when the conductors are loaded with signal voltage and flowed with signal current. Any changes to the voltage and current will result in variation of the electromagnetic field. Thus, the time-varying electromagnetic field can reflect the voltage and current variations in the cable. In view of this, the author introduced the electromagnetic theory and distributed parameter circuit model (Figure 1) to explore the signal transmission features of the RF cable.

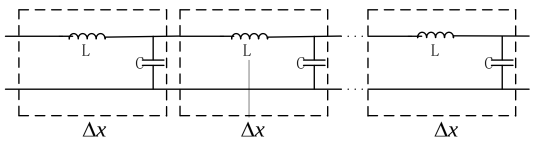

Fig.1. Distributed Parameter Circuit Model of An Ideal Rf Cable

Whereas the circuit parameters are distributed evenly across the RF cable, the voltage and current on the cable are dependent on time (t) and distance(x). If the RF cable is divided into micro-segments of the length of Δx. If Δx→0, the distribution of circuit parameters is negligible on the micro-segments, and can be replaced with a lumped parameter circuit equivalent. In this case, the entire homogenous RF cable can be regarded as a cable made up of countless Δx [14]. Figure 2 illustrates a Δx -long micro-segment of the RF cable.

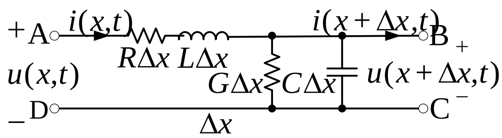

Fig.2. Micro-segment of The RF Cable

As mentioned above, the voltage and current on the cable are dependent on time and space. The dependence is a harmonic function. Thus, the insertion loss of the cable can be expressed as follows:

$$-\frac{dU(x)}{dx}=(R+j\omega L)I(x)=ZI(x) \tag{1}$$

$$-\frac{dI(x)}{dx}=(G+j\omega C)V(x)=YU(x) \tag{2}$$

where Z is the series impedance (z=jωL+R) [15]; Y is the parallel impedance (Y=jwC+G); ω is the angular frequency (ω=2πf).

Owing to the homogenous geometric and electromagnetic properties of the RF cable, the transmission parameters must be evenly distributed on the cable. To deduce the signal transmission features of these parameters, it is necessary to represent the transmission parameters as unit length of the circuit parameters. The transmission parameters include: (1) per unit length resistance R(Ω/m); (2) per unit length capacitance L(H/m); (3) per unit length leakage conductance between the inner and outer conductors C(F/m); (4) RF cable leakage conductance between the inner and outer conductors is G(S/m). The ambient temperature, signal frequency and insulating layer thickness leave an impact on the four parameters, and thereby affect the final signal transmission features. Therefore, the three influencing factors were taken into account during the analysis of the attenuation of RF cable signals.

3. Single Factor Analysis of Insertion Loss

As the object of this research, the RF coaxial cable (Figure 3) centres on an axis between the inner and outer conductors. There is also a layer of insulating material between the two conductors, which offers the outermost protection of the cable. In this structure, the outer conductor shields the influence of external electromagnetic environment on the transmitted signals, and reduces the radiation of electromagnetic energy of the cable. As a result, the signals can only be transmitted from one end to the other in the cable. The geometric parameters of the simulation model are shown in Table 1. The inner and outer conductors are made of silver-plated copper, and the insulation and jackets are made of polytetrafluoroethylene (PTFE). Table 2 lists the finite-element analysis results on material properties at ambient temperature. It should be noted that the metal activity and thermal conductivity vary with temperature, and the dielectric constant of the insulating material changes with signal frequency.

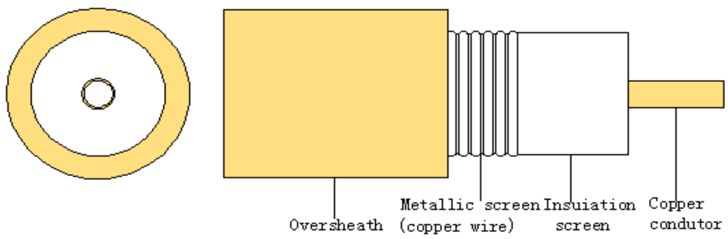

Fig.3. Simulation Model of RF Cable

Tab.1. Geometric Parameters of The Simulation Model

Factors	Insulation thickness *H(mm)*	Ambient temperature T(°C)	Signal Frequency f($\times 10^9 Hz$)
1	0.48	20	1
2	1.035	80	9
3	1.53	150	18

Tab.2. Material Properties At 20°C

Material properties	Inner conductor / shield	Insulation / jacket
Resistivity /Ω/m	$1.724e^{-8}$	-
Thermal Conductivity / $W(m\cdot K)^{-1}$	420	0.005
Specific heat coefficient / $J(kg\cdot K)^{-1}$	386	1.05
Relative permeability	1	1
Density / (kg/m^3)	8900	2200
Relative permittivity / $F\cdot m^{-1}$	1	2.1

As shown in Figure 4, a 10m SFB coaxial port of excitation load was adopted for the RF cable. The impedance at both transmitter and receiver ends was set to 50Ω, forming a complete impedance of the cable. Thus, a complete signal loop was set up in the cable. Within the two-port network, the S-parameter S_{21} represents the insertion loss of the cable. As one of the signal transmission features, the insertion loss changes with the cable structure, ambient temperature and signal frequency. Besides, the heat exchange between the outer skin of the cable and the surrounding environment was set as heat convection.

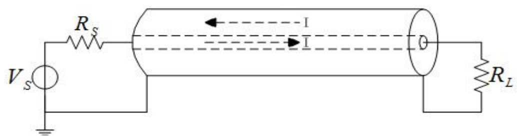

Fig.4. Signal Integrity Circuit

3.1 Effect of Signal Frequency on Signal Transmission Features of the RF Cable

With other parameters remaining the same, the signal frequency was altered from 1GHz to 18GHz to measure the insertion loss S_{21} of the RF cable with a 1.053mm-thick insulating layer. Figure 5 depicts the relationship between signal attenuation and frequency.

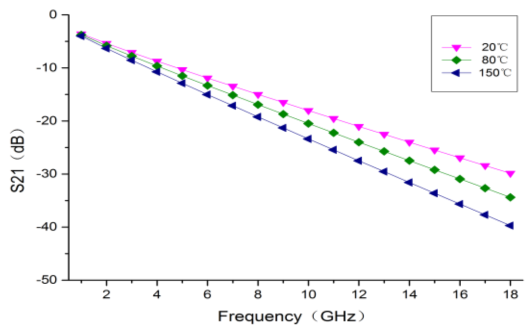

Fig.5. Relationship between Signal Attenuation and Signal Frequency

According to Figure 5, the insertion loss increased with the signal frequency of the RF cable. At a certain frequency, the cable had a skin effect [16] between the inner and outer conductors. The growth of signal frequency led to shallower skin depth, higher effective resistance of conductors, and greater signal loss on the conductors. For the insulating layer, the dielectric constant increased with the signal frequency, resulting in greater dielectric loss.

3.2 Effect of Ambient Temperature on Signal Transmission Features of the RF Cable

With other parameters remaining the same, the ambient temperature was altered from 20°C to

150°C to measure the insertion loss S_{21} of the RF cable with a 1.053mm-thick insulating layer. Figure 6 depicts the relationship between signal attenuation and ambient temperature.

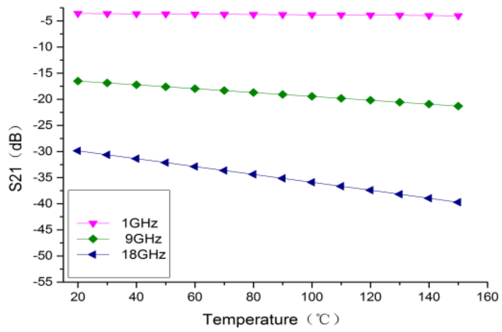

Fig.6. Relationship between Signal Attenuation and Ambient Temperature

As shown in Figure 6, the resistance of the inner and outer conductors increased with the ambient temperature. In the meantime, the rise of the ambient temperature was accompanied by the growth of the dielectric constant of the insulating layer, resulting in greater dielectric loss. Coupled with Figure 5, it is observed that the effect of ambient temperature on signal attenuation, relatively low at the signal frequency of 1GHz, became relatively significant as the signal frequency increased to 18GHz.

4. Multivariate Analysis of Signal Insertion Losses

Following the orthogonal design, the structure design, ambient temperature and signal frequency were combined in different patterns, provided that the parameters in the combination were sufficient to reflect all the information on signal transmission features of the RF cable. Then, the finite-element method was adopted to explain the signal transmission features of these parameter combinations and other conditions of the cable. Finally, the degree of influence of each parameter on the signal transmission features was identified to obtain the required combination of parameters.

4.1 Orthogonal Design

In a comprehensive multivariate test [17], the number of tests and treatments grows with the number of factors and cells, making it impossible to test all the combinations at once. Hence, the most representative parameter combinations were picked out from the orthogonal table to achieve the desired effect of multivariate test. The orthogonal table covers various factors and levels. The factors exert different impacts on the test results, and the levels represent different combinations of the factors. According to the RF cable signal attenuation, three key influencing factors on signal strength were selected: insulating layer thickness *H*, ambient temperature *T* and signal frequency *f*. Table 1 lists the three factors and three levels being selected. According to the principles of orthogonal design, the signal loss on the RF cable was simulated (Table 3).

Tab.3. Orthogonal Table and Simulated Signal Loss

Number	*H(mm)*	T(ºC)	f($\times 10^9 Hz$)	Simulation results S_{21}(dB)
1	1(0.48)	1(20)	1(1)	-6.349
2	1(0.48)	2(80)	2(9)	-23.735
3	1(0.48)	3(150)	3(18)	-45.853
4	2(1.035)	1(20)	2(9)	-16.506
5	2(1.035)	2(80)	3(18)	-34.377
6	2(1.035)	3(150)	1(1)	-3.995
7	3(1.53)	1(20)	3(18)	-27.671
8	3(1.53)	2(80)	1(1)	-2.918
9	3(1.53)	3(150)	2(9)	-19.747

Table 3 displays a total of nine different combinations of insertion losses of RF cable signals. Based on the nine different combinations, the author constructed nine 3D simulation models. The simulated insertion losses of the nine combinations are shown in Table 3. According to the table, the maximum attenuation (-45.853dB) appears in Combination 3, where the insulating layer thickness is 0.48mm, the ambient temperature is 150°C and the signal frequency is 18GHz, while the minimum attenuation (-2.918dB) appears in Combination 8, where the insulating layer thickness is 1.53mm, the ambient temperature is 80°C and the signal frequency is 1GHz.

4.2 Range Analysis of Insertion Loss

The signal transmission feature S_{21} was obtained by the orthogonal table in Table 3. The range analysis results of insertion loss are listed in Table 4.

As shown in Table 4, in terms of the effect on insertion loss S_{21}, the parameters are ranked as signal frequency *f(Hz)*>insulating layer thickness *H(mm)*>ambient temperature T(ºC) in descending order. This means the S_{21} is mainly affected by the signal frequency and least affected by the ambient temperature. Therefore, the radio frequency must be rational in the test of the environment of the RF cable.

Tab.4. Range Analysis Results of Signal Transmission Feature S_{21}

Result	Insulation thickness *H(mm)*	Ambient temperature T(ºC)	Signal frequency f(×10^9*Hz*)
T_{i1}	-75.937	-50.526	-13.262
T_{i2}	-54.878	-61.03	-59.988
T_{i3}	-50.336	-69.595	-107.901
K_{i1}	-25.312	-16.842	-4.421
K_{i2}	-18.293	-20.343	-19.996
K_{i3}	-16.779	-23.198	-35.967
R_i	8.533	6.356	31.546
Order	2	3	1

4.3 Variance Analysis of Insertion Loss

As can be seen from the previous analysis, the use of visual range analysis can quickly determine various factors depending on the size of the combinations, but the results lack accuracy and variance. In addition, important influencing factors must be determined by variance analysis.

Tab.5. Variance Analysis Results

Variance source	Sum of squares	Freedom	Estimator of variance	*F*	$F_{0.01}$	$F_{0.05}$	Significance
Insulation thickness *H(mm)*	124.3914	2	62.1957	7.6502	99.0	19.0	Non-significant
Ambient temperature T(ºC)	60.8138	2	30.4069	3.7401	99.0	19.0	Non-significant
Signal frequency $f(\times 10^9 Hz)$	1492.8348	2	746.4174	91.8114	99.0	19.0	Significant
Error Q_E	16.2598	2	8.1299				
Sum Q_T	1694.2998	8					

In this study, none of the orthogonal column is saturated. There is a blank line in each column, which can be regarded as the error term of the variance analysis of the corresponding factor. Hence, the factors should be estimated repeated to avoid the error terms. Table 5 lists the signal transmission feature S_{21} after the variance analysis of the test results.

According to Tables 4 and 5, the F-statistic of the three influencing factors on S_{21} falls between $F_{0.01}$ and $F_{0.05}$. With the F-statistic below $F_{0.05}$, the ambient temperature and the insulating layer thickness are non-significant factors. By contrast, the signal frequency boasts the most significant effect on the signal transmission feature of the RF cable.

4.4 Multivariate Linear Regression Model of the Insertion Loss

The three interaction factors A, B and C predicted in multivariate linear regression analysis [18] are listed in Table 6. According to the results of orthogonal test and variance analysis, it was assumed that there existed a strong interaction between AB, AC and BC, and a six-element subset was constructed, including A, B, C, AB, AC and BC. For better accuracy, the factors were normalized to turn the linear regression model into Y*= S_{21}, B=T, C=*f*, AB=H×T, AC= H×*f*, BC= T×*f*, etc. prior to the regression analysis. The regression model is expressed as formula (3):

$$Y^* = x_0 + x_1 A + x_2 B + x_3 C + x_4 AB \\ + x_5 AC + x_6 BC \quad (3)$$

Tab.6. Linear Regression Model of Insertion Loss of the RF Cable

Statistical regression				
Multiple correlation coefficient R			0.9985	
Standard error			1.5857	
Observations			9.0000	
ANOVA	DF	SS	MS	F
Regression analysis	6	1689.2705	281.5451	111.9657
Residuals	2	5.0291	2.5146	
Sum	8	1694.2996		
Parameter	Coefficients	Standard error	t Stat	P-value
x_0	-6.5657	2.7321	-2.4031	0.1382
x_1	3.0734	3.2815	0.9366	0.4478
x_2	-0.0054	0.0416	-0.1293	0.9090
x_3	-1.5710	0.6137	-2.5600	0.1247
x_4	0.0103	0.0432	0.2390	0.8334
x_5	0.1647	0.3565	0.4619	0.6895
x_6	-0.0051	0.0027	-1.9254	0.1940

The regression equation is:

$$Y^* = -6.5657 + 3.0734H - 0.0054T - 1.751f \\ + 0.0103HT + 0.1647Hf - 0.0051Tf \quad (4)$$

From the above formula, it is easy to compute the S_{21} at different variables. Then, the author carried out an experiment to verify the accuracy of formula (4). The results obtained in the experiment and the calculated results of the regression equation are shown in Table 7.

Tab.7. Comparison between Experimental Results with Regression Results

Number	Experimental factors			S_{21}(dB)		
	H(mm)	T(℃)	$f(\times 10^9 Hz)$	Experiment Result	Fitting Result	Absolute error
1	0.48	20	1	-6.178	-6.349	-0.171
2	0.48	80	9	-24.136	-22.226	1.91
3	0.48	150	18	-42.953	-45.784	-2.831
4	1.035	20	9	-17.83	-16.802	1.028
5	1.035	80	18	-34.275	-35.518	-1.243
6	1.035	150	1	-4.495	-4.761	-0.266
7	1.53	20	18	-28.942	-27.234	1.708
8	1.53	80	1	-2.928	-2.762	0.166
9	1.53	150	9	-18.115	-19.066	-0.951

Table 7 shows that the deviation between the experimental results and the regression results falls within the allowable range, indicating that the regression equation fit well with the experimental results.

Conclusions

The following conclusions were drawn through the research.

(1) The cable size, the ambient temperature and signal frequency are three influencing factors on the insertion loss S_{21} of the signal. By changing one factor at a time, it is learned that insertion loss decreases with the increase in insulating layer thickness. In other words, the RF cable signal attenuates slower with the thickening of the insulting layer. Moreover, the insertion loss and the signal attenuation increase with the ambient temperature and signal frequency.

(2) The orthogonal test reveals that: in terms of the effect on insertion loss, the parameters are ranked as signal frequency>insulating layer thickness>ambient temperature in descending order. Besides, the minimum attenuation (-2.918dB) appears in the combination where the insulating layer thickness is 1.53mm, the ambient temperature is 80°C and the signal frequency is 1GHz.

(3) To disclose the signal transmission features of insulating layer thickness, ambient temperature, and signal frequency, the author constructed a regression model based on simulation and experiment: $Y^*=-6.5657+3.0734H-0.0054T-1.751f+0.0103HT+0.1647Hf-0.0051Tf$, and verified the effectiveness of the model through experiment.

ACKNOWLEDGMENTS

The Project was supported by the Scientific research program Funded By Hubei Provincial Department Of Education (No.B2017502).

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