AIAA AVIATION Forum
13-17 June 2016, Washington, D.C.
AIAA Modeling and Simulation Technologies Conference

10.2514/6.2016-4137

Component-level Modeling and Simulation of Cable Fault Detection System

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To solve the serious problems produced by cable faults, research on modeling and simulation of cable fault detection system is carried out in this paper. In order to realize correct judgement of fault types and accurate positioning of fault distance, component-level modeling method is applied in the article. Based on Spread Spectrum Time Domain Reflectometry (SSTDR) method, starting from aspects of incident signal's generation, realization of isolated coupling, equivalent of test cable system and analog of cable faults, the model of cable fault online detection system is established in Simulink. Simulation result shows that cable fault can be detected correctly, which indicates that the built model can accurately represent characteristic of the cable fault. The work lays the foundation for further study of cable fault detection.

Nomenclature

SSTDR	=	Spread Spectrum Time Domain Reflectometry
BPSK	=	Binary Phase Shift Keying
C_0	=	Capacitance per unit length
L_0	=	Inductance per unit length
R_0	=	Resistance per unit length
G_0	=	Conductivity per unit length
r	=	Radius of cable conductor
ζ	=	Skin depth
ρ	=	Electric conductivity
s	=	Distance between two conductors
ε_0	=	Dielectric constant
ε_r	=	Relative dielectric constant
μ_0	=	Permeability of vaccun
μ_r	=	Relative magnetic permeability
R_a	=	Inside radius of shielding layer about coaxial cable
R_b	=	Outside radius of shielding layer about coaxial cable

I. Introduction

WITH the development of more/all electric aircrafts, electrical equipments become more and more widely used, and the use of cables is increasing rapidly. As time goes, complex factors like water, ultraviolet ray, temperature, vibration, overload, and aging may lead cables to crack and wear. The cable failures like

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open faults, short faults and intermittent faults will happen. All of these faults will pose great threatens to the normal work of aircrafts. So an effective cable fault detection system is essential, which is of great help to study cable's fault signatures and realize cable fault diagnosis.

Research on the modeling of cable fault detection is numerous both in domestic and at abroad. In the document [8], researchers in Canada took study on cable television network fault detection, which with the help of two model engines, the one is neural network and the other one is statistical analysis technology. However, both that two modeling methods can't realize cable fault location accurately. In the reference [9], researchers in Beijing Sifang Automation did research on simplified model of distribution network, modeling and simulation is down according to the structure and characteristics of transmission nework, which is based on the minimum area consisting of minimum power supply for controlling and operating. This method reduced the complexity of system modeling, however, to the detection of parts in the minimum area is helpless, so it is unable to diagnose cable faults. And to the detection of cable fault detection and location, in the document [10], National Insititute of Technology in India studied the detection and location of faults in underground cable using MATLAB/Simulink, ANN(Artificial Neural Network) and OrCad, which realized cable fault detection whatever fault type or fault location. Yet, the whole implementation process steps are numerous, its algorithm is complex and it is not conducive to the realization of actual hardware. Therefore, research a simple and visual modeling method to realize cable fault location is necessary.

At present, models can be categorized into four levels, i.e., component, behavioral, functional, and architectural levels. Among these approaches, the behavioral-level modeling is based on the aspect of describing a specific input/output behavior, which is suitable for the simulation of system level. The functional-level model usually adopt analytical expressions like transfer functions to describe characteristic of the components. And architectural-level model can just stand out the steady-state characteristics of modeled targets. However, the component-level model is based on the principle of circuits, which can represent the characteristic of cable fault completely and clearly. So it is suitable to model cable fault detection system. Among the software of modeling and simulation, MATLAB has the strong ability of numerical calculation and the perfect PSB library, so it is chosen in modeling and simulation. Nowadays, commonly used cable fault diagnosis includes bridge method, traveling wave method, reflection method, etc. In the forms of reflection methods, SSTDR not only can detect the faults online, but also have advantages of high positioning accuracy and strong anti-jamming capability. Therefore, in this paper, based on the method of SSTDR, modeling and simulation of cable fault detection system by Simulink is researched.

II. Modeling of Cable Fault Detection System

A. Theory and Realization of Cable Fault Detection

Fig.1 shows the schematic diagram of the model about SSTDR cable fault detection. Based on the theory of reflectrometry, which is realized by three steps: 1) the signal source injects spread spectrum signal into the test cable, 2) the detector collects the reflected signal coming from the place where the fault occurs and the impedance is mismatch, and 3) correlation calculations are undertaken with incident signal and reflected signal. According to the amplitude and time delay of reflected signal compared with incident signal, fault type and fault distance can be diagnosed.

According to the theory of cable fault diagnosis, SSTDR detection system includes the incident signal module, the isolated coupling module, test cable, fault point and fault information extraction module. Among those modules, the incident signal is a kind of spread spectrum signal, which is modulated by m sequence and sine wave. Isolated coupling module isolates strong and weak electricity, and realizes the signals' bi-directional coupling, which means that it transmits incident signal to the cable on test and receives reflected signal coming from fault point. Test cable model's establishment is based on practical distribution parameters of the wire. The fault includs open circuit and short circuit. And fault information extraction module processes incident signal and reflected signal, then fault information of fault type and fault distance can be got.

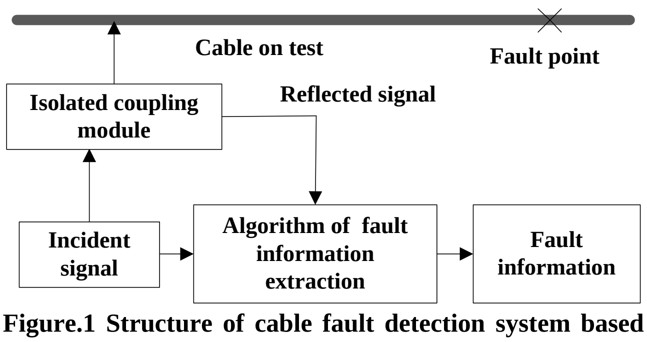


Figure.1 Structure of cable fault detection system based on SSTDR

B. Modeling of Incident Signal

According to the generation of incident signal about SSTDR, it can be found that incident signal module consists of three parts, the module of m sequence, sine wave and spread spectrum modulation.

1) m sequence generation module. m sequence is a kind of pseudo-random code, which can not be pre-determined but can be reproduced. It is generated by n order linear feedback shift register (LFSR) whose cycle is 2^n-1.In this paper, m sequence is realized by seven order shift register, which generates a 7th-order primitive polynomial containing 1st-order, 2nd-order, 3rd-order and 7th-order terms, and the number of PN code is 127.

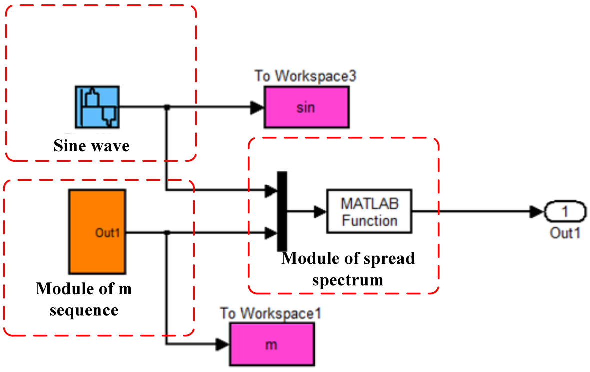


Figure.2 The model of incident signal

2) Sine wave generation module. The generation of sine wave in MATLAB is simple, which can be got in MATLAB/Simulink library.

3) Spread spectrum modulation. The theory of binary phase shift keying modulation (BPSK) is as follows.While m sequence is in high level, phase of sine wave remains unchanged. On the contrary, when m sequence is in low level, inversing sine wave.

Fig. 2 shows the established model of incident signal in MATLAB/Simulink. In the system, the frequency of sine wave is set to be 30MHz, bandwidth of m sequence is 0-30MHz. So in theory, modulated signal's bandwidth will be 0-60MHz, its waveform of modulated signal will be given in part III.

C. Modeling of Isolated Coupling Module

To achieve the function of electrical isolation, an radio-frequency transformer is needed. It is used to inject incident signal to test cable and gather reflected signal coming from fault point. The primary side of transformer is of double winding structure and secondary side is of single winding structure, parameters set of three windings are the same. Ideal transformer is formed with original winding 1 and auxiliary winding 2, which is aimed at coupling detection signal to test cable. At the same time, ideal transformer with original winding 3 and auxiliary winding 2 is formed to couple reflected signal out. In addition, an high voltage capacitor C is essential in the isolated coupling module, which is used to filter out signal of low frequency and realize the strong and weak electrical isolation. Resistor *Rs* between incident signal module and isolated coupling module is the matching resistance, whose value equals the characteristic impedance of test cable, and P1 is the interface together with test cable. The diagram of isolated coupling model is shown in Fig. 3.

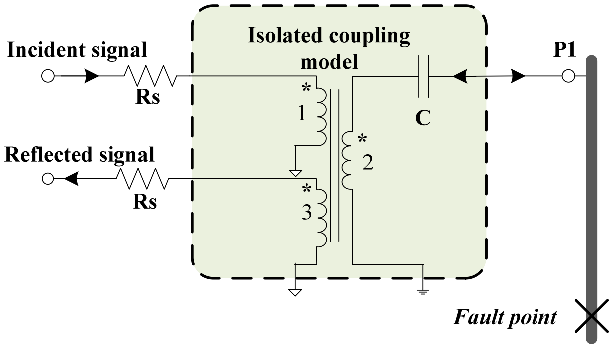


Figure.3 Isolated coupling model

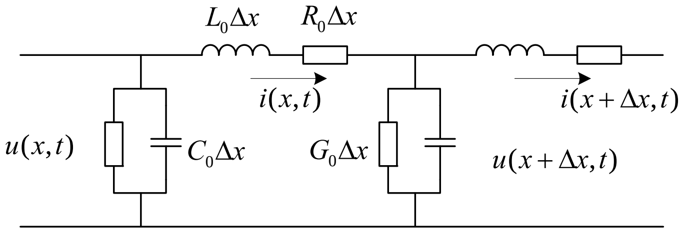


Figure.4 The model of test cable with distribution parameter

D. The Model of Cable System and Fault Point

1) The model of cable system

Since the incident signal is a kind of broadband carrier signal whose wavelength is not greater than the length of cable, it is assumed that cable is a kind of uniform medium, so the test cable can be equivalent to a transmission line. And detection signal transmitting in the test cable can be analyzed by the theory of transmission line.

Fig.4 shows the model of transmission line. C_0, L_0, R_0 and G_0 is respectively the distributed parameter of the capacitance, inductance, resistance and conductivity. Transmission line can be seen as many tiny line elements, and each line element can be regard as lumped circuits. The value of conductivity is so small that it can be ignored. Table I shows the distributed parameter calculation formulas of coaxial cable and double pole type cable.

2) The model of fault point

The main kinds of fault are open-circuit fault and short-circuit fault. The former one presents the state of high impedance while the later one presents the state of low impedance.

Table I Distributed parameter calculation formula of double pole type and coaxial cable

	double pole type	coaxial
resistor	$R_0 = 2\times\frac{\rho}{\pi r^2 - \pi(r-\varsigma)^2}$	$R_0 = \frac{\rho}{\pi r^2 - \pi(r-\varsigma)^2}$
inductance	$L_0 = \frac{\mu_0\mu_r}{\pi}\ln\left(\frac{s}{2r}+\sqrt{(\frac{s}{2r})^2-1}\right)$	$L_0 = \frac{\mu_0\mu_r}{2\pi}\ln\left(\frac{R_b}{R_a}\right)$
capacitance	$C_0 = \frac{\pi\varepsilon_r\varepsilon_0}{\ln\left(\frac{s}{2r}+\sqrt{(\frac{s}{2r})^2-1}\right)}$	$C_0 = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\left(\frac{R_b}{R_a}\right)}$

E. SSTDR Cable Fault Online Detection Model

The whole model of the cable fault detection system established in MATLAB/Simulink is shown in Fig.5, including incident signal module, isolated coupling module, test cable system, fault point and fault information processing module. Among those modules, the fault information processing module is realized with algorithm, therefore it will not be detailed here.

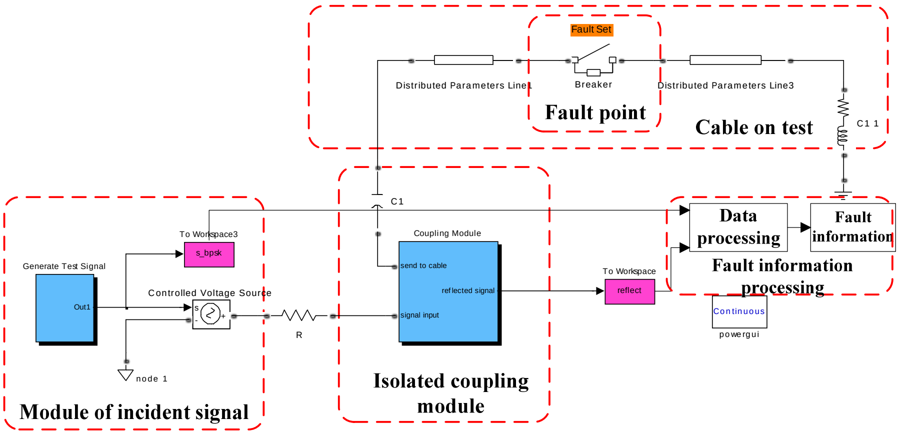


Figure.5 Model of the cable fault detection system

III. Simulation of Cable Fault Detection System

To verify the correctness and feasibility of SSTDR cable fault detection system, waveform of incident signal produced by incident signal model is simulated firstly. Then, the whole model used in cable fault diagnosis is simulated.

A. Simulation of Incident Signal

1) Simulation of m sequence module

In order to ensure that 7th-order m sequence module can produce 127 bit PN code and can be reproduced, waveform of m sequence is simulated in two cycles of time. As to facilitate observation, m sequence code cycle T_C is set to be 1s and

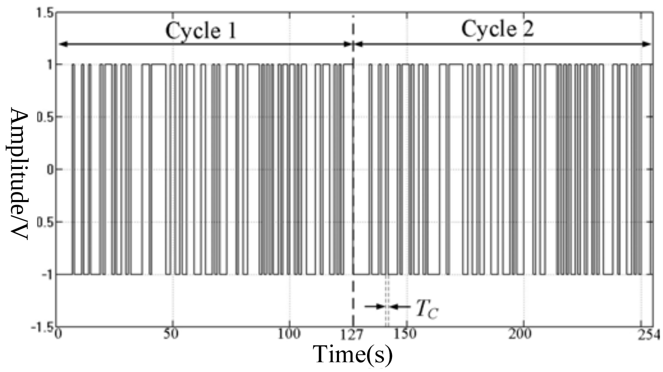
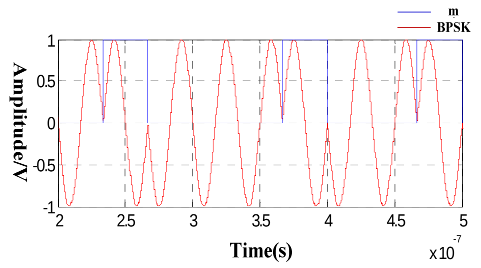


Figure.6 Waveform of m sequence with two cycles of time

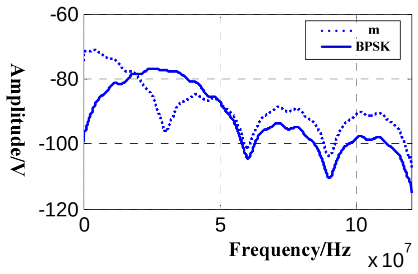
simulation time is set to be 254s. Simulation result is shown in Fig. 6.

According to Fig.6, it can be found that m sequence is successfully produced, one cycle of m sequence includes 127 PN code. And m sequence waveforms of two cycles are the same, which verifies that m sequence can be reproduced. Simulation reveals that the established m sequence module is correct.

2) Simulation of BPSK modulation waveform



(a) BPSK modulation waveform



(b) Frequency spectrum of BPSK modulation waveform

Figure 7 Simulation waveform and frequency spectrum of BPSK

Fig.7 shows the waveforms of m sequence, modulated incident signal and their frequency spectrum analytical result. Simulation demomstrates that the incident signal model can successfully generate BPSK signal, through the spectrum analysis, and it can be found that bandwidth of modulated signal is 0-60MHz, which is compatible with theoretical analysis in Section II.

B. Simulation about Cable Fault Diagnosis with the Whole System Model

To verify the correctness of established system model, open-circuit fault and short-circuit fault are set in the test cable, simulations of cable fault detection are done. Respectively setting open fault at the point of 3 meters, 4 meters, 5 meters, 6 meters and 7 meters, simulation results are shown in Fig. 8 and Fig. 9.

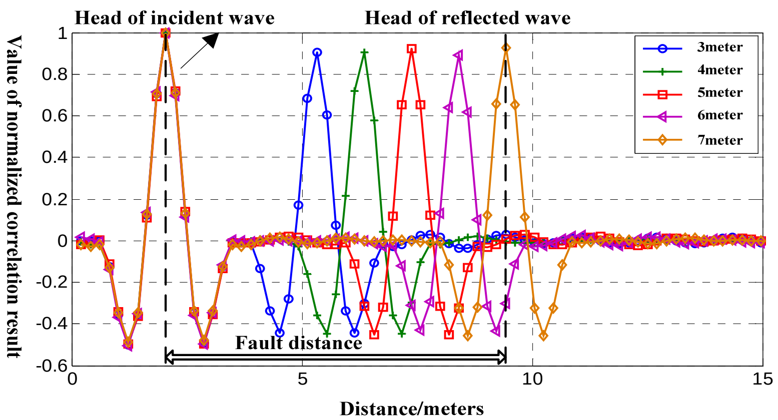


Figure.8 Simulation results of open-circuit fault detection

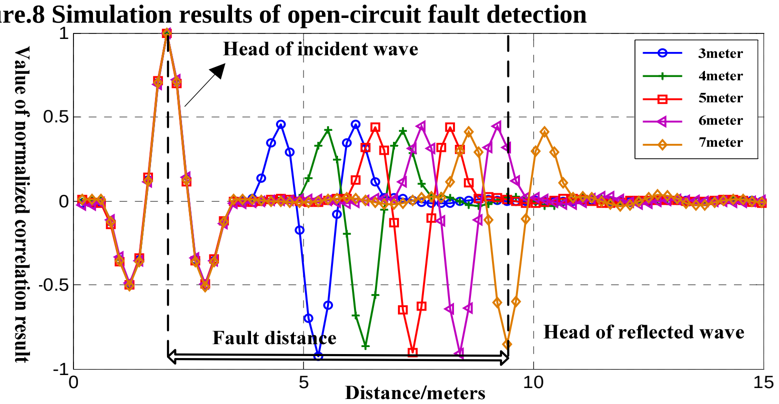


Figure.9 Simulation results of short fault detection

According to the results, as for any single-colored curve, the head of reflected wave shows the type of the fault, the distance between the head of incident wave and reflected wave shows the fault distance. When an open-circuit fault occurs, the incident wave and reflected wave are of the same direction. When a short-circuit fault happens, the two waves are of opposite directions, which is in line with the traveling wave reflection principle, it illustrates the established model can correctly judge cable fault type. Also, the location of the fault detected is similar to the fault location that is set. The result of the simulation shows the correctness of the established model of cable fault detection system.

IV. Conclusion

The model of cable fault detection system is established and the simulation of cable fault diagnosis is done in this paper. Result shows that just with the software of MATLAB/Simulink, the model can represent the characteristic of cable fault accurately, and the feasibility of cable fault detection by SSTDR is also verified. It verified the correctness of component-level modeling on cable fault detection system, its implementation is simple and diagnosis of waveform is direct. All of those above lay the foundation for further researches on the cable fault detection, such as the diagnosis of multiple cables and non-contact diagnosis of cable fault detection, which have theoretical guidance significance for practical application.

Acknowledgments

Research reported in this paper was supported by the National Natural Science Foundation of China (51277093).

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