Research on detection method for aviation bus based on electrical characteristics

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Abstract. Based on the current situation of aviation bus detection, this paper analyzes the application limitations and shortcomings of existing detection methods. On this basis, an improved detection method in frequency-domain for two common aviation buses with different structures based on TDR technology is designed, and the detection of hard faults is used as an example to explain the detection strategy, application difficulties and solutions. Besides, the detection of soft faults for aviation bus are emphatically studied based on this method. The experimental results show that the scheme has high feasibility and good diagnostic accuracy, which provides an important reference value in engineering for reducing the difficulty and improving the efficiency of electrical fault detection for aviation bus.

1. Introduction
As a communication hub between various equipment of the aircraft, the aviation bus is responsible for signal transmission and distribution, which is a crucial part of the aircraft[1]. Cables are used throughout the aircraft. Due to the structural characteristics of the aircraft, there are restrictions on the volume and weight of the cables. Therefore, the aviation bus with smaller diameter and thinner insulation layer is required. In addition, long-term vibration, corrosion and aging during flight missions causes frequent electrical faults in cables. Each year, the US Navy cancels more than 100,000 hours of flight missions, requiring maintenance personnel to spend nearly 2 million hours detecting and repairing failures caused by cable faults. Therefore, the diagnosis and analysis of aviation bus faults has become a hot topic in current research.

The existing detection methods for aviation bus mainly focus on the tests of static electrical continuity when the cable is shipped, waveform distortion during signal transmission[2][3]. Due to the small space, irregular wiring, and complex cable characteristics, it is difficult to locate and diagnose fault types of the cables which are already equipped on aircraft, especially fighters and there are few detection methods.

The faults of aviation buses can be divided into two categories based on their severity, namely, hard faults such as short circuit and open circuit, and soft faults such as impedance mismatch. The harm of hard faults is obvious, which will make the equipment work improperly and communication fail, thus it is a type of fault that must be eliminated as soon as possible. Soft faults such as cable bending, wear of the protective layer, damage to the shielding layer, and poor contact between conductors caused by improper use, aging, abrasion, etc. will not only lead to bad performance of communication systems, but also gradually accumulate into hard faults, so that the equipment cannot work properly and even
accidents occur. Therefore, comprehensive detection and analysis of the soft and hard faults are of great significance to the stable operation of the aviation bus system and the prevention of accidents. Based on the analysis of the existing detection methods, this paper considers the detection needs comprehensively, designs a detection method for aviation bus in frequency domain, and focuses on the research of the soft fault detection based on it.

2. Problem description
At present, there are two common methods for detecting electrical characteristics of the aviation bus: one is manual multi-point measurement, which has the disadvantages such as high error rate and low efficiency, but it is still used for cable detection in factory because of its low cost and easy operation. The other method, time domain reflectometry (TDR), is relatively efficient [3-4]. It only needs to inject a step signal at one end, and then observe the reflected signal to judge the fault type and calculate its distance based on experience. However, this method requires strict rise time of the injected signal. If the rise time is too long, the resolution of the TDR system will be insufficient, which means that some feature points will be hidden, and the fault cannot be diagnosed. In order to ensure a faster rise time, the use of the protection circuit must be minimized as much as possible, which results in the sampling probe being extremely susceptible to electrostatic breakdown or EOS overwork damage caused by charge accumulation.

In general, the characteristics of soft faults are not obvious, so it is difficult to locate and diagnose them. At present, only a few domestic and foreign researchers have carried out relevant studies on soft fault detection for aviation bus [5-7], and the existing results are mainly in the stage of theoretical verification, which means there is no effective solution for soft fault detection in practical applications. It is known that the fault affects the impedance of the cable, and when the instantaneous impedance of a certain point is mismatched with the characteristic impedance of the cable, the reflection characteristics will change. The frequency-domain information (S parameter) is a network parameter based on the relationship between the incident wave and the reflected wave. Among the S parameters, $S_{11}$ and $S_{22}$ are reflection coefficients, representing the return loss, that is, the energy reflected back to the source. $S_{12} / S_{21}$ is the inverse/forward transmission coefficient, which represents the transmission gain, that is, the energy transmitted to the destination. Which means, the fault information will be reflected in the change of $S_{11}$ and $S_{22}$ parameters directly. By converting this frequency domain information into time domain information with the mathematical method, the problem that TDR sampling probe is easy to be burned out is solved, and the purpose of locating faults in the time domain is also achieved. Therefore this scheme is to realize the detection of aviation bus based on the measurement and analysis of S parameters.

However, because the fault characteristics of soft one are not obvious in general, the fault information is easily weakened by the attenuation of cable itself during the detection process, even buried in the noise. Therefore, it is impossible to diagnose soft faults by analyzing the measured S parameters directly. In addition, when this method is applied to detect the twisted-pair cable, such as 1553B bus, there are two problems, that is, the mismatched characteristic impedance and the unpaired connectors between the detecting device and the cable to be tested. In the following, the detection methods of soft and hard faults for the aviation bus will be introduced respectively by describing the detection strategies, application difficulties and solutions.

3. Research on hard fault detection for aviation bus
For the fault detection of the coaxial aviation bus, after obtaining the two-port S parameters by operating a vector network analyzer, the IFFT is used to transform the frequency domain information into time domain information which characterizes the fault location. Two types of TDR curves, open circuit and short circuit, are shown in figure 1 in turn.
According to $S_{11} = \frac{Z - Z_0}{Z + Z_0}$, when there is a fault of open circuit in the cable, $Z$ becomes larger, the reflection coefficient is close to 1, and more energy is reflected back to the source. The vertical axis of the TDR curve represents the amplitude of the reflected voltage, so the fault of open circuit is reflected in the TDR curve rising after the open point. However, when there is a fault of short circuit in the cable, $Z$ is close to 0, the reflection coefficient is around -1, and the energy reflected back to the source reduces, which means that the TDR curve falls after the short point. It can be seen from Figure 1 that open-circuit and short-circuit phenomena are obvious and easy to judge.

For another type of aviation bus 1553B, it is a shielded twisted-pair cable with a characteristic impedance of 75ohm and its connector is a triaxial connector, while the common vector network analyzer has a characteristic impedance of 50 ohm, and the connector is a coaxial connector. In order to solve the problem of impedance matching, the method adopted in this paper is to test the cable by considering its characteristic impedance as 50 ohms, and then convert the measured $S$ parameter with a characteristic impedance of 50 ohms into the one with 75 ohms by mathematical method, thus avoiding the large attenuation brought by the impedance converter. Aiming at the problem of interface mismatch, this scheme designs a conversion connector to convert one triaxial to two dual coaxial, and then repeats the above steps twice to measure the $S$ parameters of the four ports of the 1553B cable according to the dual-coaxial mechanism. Taking the single-line short circuit and the dual-line open circuit as examples, their TDR diagrams are shown in figure 2, respectively.

As can be seen from figure 2, the two cable adapters can be clearly positioned, the 1553B cable between them has obvious fault characteristics, so that the fault can be located and diagnosed accurately.

Compared with the TDR method, the scheme not only increases the safety, but also expands the number of faults that can be detected in one test and improves the efficiency of detection. If there are multiple faults on the single line of the 1553B cable, when measuring the $S$ parameter of a "coaxial line", the reflection coefficient of both ends can be obtained at the same time, and then the mathematical methods can be used to get the information of the first fault of each end. However, if it is implemented by the TDR method, signals need to be injected into the two ends respectively to perform two detections. By analogy, for one detection of the 1553B cable, up to four fault can be found, which makes sense for efficient detection of two/multi-line cables.

4. Research on soft fault detection for aviation bus
Based on the above-mentioned detection method in frequency domain, aiming at the problem that characteristics of the soft fault are not obvious, this section analyzes the characteristic compensation mechanism, introduces the detection method of soft faults in detail and uses a typical example in the project for algorithm verification.

4.1. Compensation mechanism of soft fault

For the ideal cable, the changes of reflection coefficient and transmission coefficient should all come from the impact of the fault, but in practical applications, the inherent loss of the cable itself also affects the measured characteristic data. For soft faults whose characteristics are not obvious, the influence of the inherent return loss of the cable can even cover the impact of impedance changes at the fault, which makes the characteristic point of the reflection coefficient unclear, so it is difficult to identify the fault feature. Therefore, in the following, first, the inherent loss of the cable is analyzed based on its structure and electrical characteristics, and then this inherent loss is compensated according to the measurement principle of required S parameter and signal transmission principle. Finally, the analysis of the reflection coefficient is performed to detect the soft fault.

4.2. The detection method of soft fault

4.2.1. Analysis of inherent loss of cable. The attenuation of the cable is mainly composed of three parts, namely resistance loss, dielectric loss and radiation loss. The effects of these three attenuations vary with the type of cable. Taking the non-leakage coaxial cable commonly used as an example, since the outer conductor has a good shielding effect, the radiation loss can be ignored basically, so its attenuation mainly comes from the resistance loss and dielectric loss.

According to the transmission line theory, the real part $\alpha$ of the propagation coefficient $\gamma$ is the attenuation constant of the cable, which represents the attenuation proportion of the electrical signal during the propagation process, which can be expressed as

$$\gamma = \alpha + i\beta = \left[ (R + i\omega L)(G + i\omega L) \right]^{1/2}$$

$$\alpha = \left[ 0.5 \left[ RG - \omega^2 LC + \left( R^2 + \omega^2 L^2 \right) \left( G^2 + \omega^2 C^2 \right) \right]^{1/2} \right]^{1/2}$$

In practical application, the coaxial cable works at high frequency, and there should be $\omega L \geq R$, $\omega C \geq G$, so equation (2) can be approximately denoted as

$$\alpha = \frac{R}{2} \left( \frac{C}{L} \right)^{1/2} + \frac{G}{2} \left( \frac{L}{C} \right)^{1/2}$$

Transmission line theory states that the characteristic impedance of a cable can be shown as

$$Z_c = \left( \frac{R + j\omega L}{G + j\omega C} \right)^{1/2}$$

Similarly, due to the high working frequency, $Z_c$ can be approximately expressed as $Z_c = \sqrt{L/C}$, which is a constant value, substituting it into equation (3), obtain

$$\alpha = \alpha_1 + \alpha_2 = 0.5 \left( R/Z_c + GZ_c \right)$$

It can be seen that the attenuation constant is only related to the equivalent resistance and insulation conductance of the cable. The equivalent resistance is determined by the conductor of the cable, while the insulation conductance is affected by the insulation medium of the cable. $\alpha_1$ and $\alpha_2$ represent the attenuation caused by the conductor loss source and the insulation dielectric loss source, respectively. For different working frequencies, the cable attenuation per unit length can be approximated by

$$\alpha = k_1 \sqrt{f} + k_2 f$$

Where, $\alpha$ represents the attenuation value at the frequency $f$; $k_1$, $k_2$ are coefficients, corresponding to the above two items respectively, which are determined by the structure and material characteristics
of the cable, so for the same section of cable, the values of \( k_1 \), \( k_2 \) remain unchanged at different frequencies. The coefficients \( k_1 \) and \( k_2 \) are respectively

\[
\begin{align*}
  k_1 &= \frac{2.61 \times \sqrt{\varepsilon} \times 10^{-6}}{\text{lg} \left( \frac{D + 1.5d_w}{K_d} \right)} \times \left( \frac{K_2 K_{\rho 1}}{d} + \frac{K_2 K_{\rho 2}}{D} \right) \\
  k_2 &= 9.10 \times \sqrt{\varepsilon} \times \text{tg} \delta \times 10^{-8}
\end{align*}
\]  

(7)

Among them, \( d \) is the diameter of the inner conductor, \( D \) is the diameter of the outer insulation, \( d_w \) is the diameter of the outer conductor for weaving, \( \varepsilon \) is the equivalent dielectric constant of the insulating material; \( \text{tg} \delta \) is the tangent of dielectric loss angle, \( K_1 \) is the diameter coefficient of the inner conductor, \( K_2 \) is the stranding coefficient of the inner conductor, \( K_b \) is the weaving effect coefficient of the outer conductor \( K_b = 1.5 + 0.083D \), \( K_{\rho 1} \) and \( K_{\rho 2} \) are the coefficients of resistance increase of the inner and outer conductors relative to the soft copper, respectively.

4.2.2. Soft fault feature compensation scheme. After obtaining the inherent loss of cable per unit length, it is necessary to study the measuring mechanism of \( S \) parameter and the transmission process of the signal, so as to compensate the measured \( S \) parameter according to the actual loss length, weaken the influence of the cable’s inherent loss, and amplify the fault characteristics introduced by soft fault.

As shown in figure 3, \( A_m \) and \( B_m \) are the incident signals generated by the excitation source of vector network analyzer, while \( A_{\text{out}} \) and \( B_{\text{out}} \) represent the reflected signals generated by the incident signal entering the cable under test, so the \( S \) parameters can be calculated by equation (9).

\[
\begin{align*}
  S_{11} &= \frac{A_{\text{out}}}{A_m} (B_m = 0), S_{21} &= \frac{B_{\text{out}}}{A_m} (B_m = 0)
\end{align*}
\]  

(9)

It can be seen from equation (9) that the amplitude of insertion loss \( S_{21} \) has the same meaning and value as the attenuation coefficient \( \alpha \) for the cable per unit length. The \( S_{21} \) amplitude of the cable per unit length can be calculated by \( |S_{21}| = 20 \times \text{lg} (b/a) \), where \( b \) is the output signal and \( a \) is the input signal. In the case of impedance mismatch occurring at length \( L \), the transmissivity \( b/a \) can be expressed as

\[
\frac{b}{a} = 10^{-\frac{\alpha L}{20}}
\]  

(10)

For any point of the cable, the sum of reflectivity and transmissivity is 1, so in the position where the impedance does not match, the reflectivity can be expressed as

\[
\frac{\alpha'}{a} = 10^{-\frac{\alpha L}{20}}
\]  

(11)

By analogy, the reflected signal \( \Gamma_a \) and transmitted signal \( T_a \) at any position \( L \) in figure 3 are respectively

\[
\begin{align*}
  T_i &= T_{i-1} \cdot 10^{-\frac{\alpha (L_i - L_{i-1})}{20}} = A_m \cdot 10^{-\frac{\alpha L_i}{20}} = A_m \cdot 10^{-\frac{\alpha L_i}{20}}
  \Gamma_i &= T_{i-1} \left( 1 - 10^{-\frac{\alpha (L_i - L_{i-1})}{20}} \right) = A_m \cdot 10^{-\frac{\alpha L_i}{20}} \left( 1 - 10^{-\frac{\alpha L_i}{20}} \right)
\end{align*}
\]  

(12)

(13)
Within the working frequency range of the cable, the attenuation of the signal is limited, so the multiple reflection phenomenon in this method can be ignored. Considering that $A_{\text{out}}$ is only the superposition of all the first reflected signals, then the signal $\Gamma_{iL}^{\alpha}$ reflected from $L_i$ back to the starting position can be calculated as

$$
\Gamma_{iL}^{\alpha} = \Gamma_{iL} \cdot T_{iL} \cdot A_{\text{in}} \cdot 10^{\frac{a_{L_{i+1}}}{20}} \cdot \left(1 - 10^\frac{a(L_{i-1} + L_{i+1})}{20}\right) \cdot 10^{\frac{a_{L_i + L_{i+1}}}{20}} = A_{\text{in}} \cdot 10^{\frac{2a_{L_{i+1}}}{20} - \frac{a(L_{i-1} + L_{i+1})}{20}}
$$

(14)

Therefore, the sum of all the reflected signals $A_{\text{out}}$ received at the beginning can be expressed as

$$
A_{\text{out}} = \sum_{i=1}^{n} \Gamma_{iL}^{\alpha} = \sum_{i=1}^{n} \left(10^{\frac{2a_{L_{i+1}}}{20} - \frac{a(L_{i-1} + L_{i+1})}{20}}\right) \cdot A_{\text{in}}
$$

(15)

The transmitted signal $B_{\text{out}}$ received at the end can be expressed as

$$
B_{\text{out}} = A_{\text{in}} \cdot 10^{\frac{a_{L_1}}{20}}
$$

(16)

It can be obtained that the intrinsic insertion loss of the lossy cable is $B_{\text{out}} / A_{\text{in}}$, and the intrinsic return loss is $A_{\text{out}} / A_{\text{in}}$. For $S_{11}$ and $S_{21}$ obtained from actual measurement, the inherent loss of the cable itself is compensated by the following formula, and the equivalent $S'_{11}$ and $S'_{21}$ determined by impedance mismatch under ideal non-destructive conditions can be obtained as

$$
S'_{11} = \frac{S_{11}}{A_{\text{out}} / A_{\text{in}}}
$$

(17)

$$
S'_{21} = \frac{S_{21}}{B_{\text{out}} / A_{\text{in}}}
$$

(18)

Considering that there is also return loss in the process of signal reflection caused by impedance mismatch, the $S'_{11}$ parameters of the cable with a fault at $L_j$ should be compensated twice.

$$
S''_{11} = \frac{S'_{11}}{10^{\frac{a_{L_j}}{20}}}
$$

(19)

After the primary and secondary compensation to the measured $S$ parameters, they can be considered as the characteristic parameters of the ideal lossless cable. Therefore, the change of the reflection characteristics caused by the soft fault is not easily submerged by the inherent loss, and the purpose of identifying the characteristic values of soft fault achieves.

### 4.3. case analysis

This section takes a common type of soft faults in aviation bus applications as an example to verify the algorithm. Common coaxial cables are divided into two types, which have the impedance of 50ohm and 75ohm, for example, RG316 and RG179. The appearance of the two is not significantly different, thus it is easy to mix and connect the two types of coaxial cables due to manual errors. Signals can still be transmitted in such case, but the transmission performance is poor, which is a typical type of soft fault that must be eliminated.

Taking coaxial cable RG316 as an example, the parameters required in its attenuation constant equation are shown in the table 1.

| $d$(mm) | $D$(mm) | $d_w$(mm) | $\varepsilon$ | $\tan \delta$ | $K_1$ | $K_2$ | $K_b$ | $K_{\rho 1}$ | $K_{\rho 2}$ |
|---------|---------|-----------|--------------|-------------|-------|-------|-------|-------------|-------------|
| 0.52    | 1.52    | 0.1       | 2.3          | 0.0002      | 0.939 | 1.3   | 1.626 | 1           | 1           |

Taking 1m RG316 coaxial cable as an example, the inherent loss is calculated and compensated according to the equations in the previous section. The comparison of the transmission coefficient...
before and after compensation is shown in Figure 4. In the ideal lossless cable, all signals should be transmitted to the end, that is, the transmission coefficient should be close to 1. However, because only two kinds of losses are considered in this method, the transmission coefficient cannot be fully compensated to 1, but it is above 0.95 when the frequency is less than 2GHz, which has achieved the purpose of compensating most of the insertion loss.

![Transmission Coefficient Comparison](image)

**Figure 4.** Comparison of the transmission coefficient before and after compensation.

This article sets up an application scenario where two 10m 50ohm coaxial lines are connected by a 1m 75ohm coaxial line to simulate such a typical soft fault. The sweep signal with the frequency during 1.5MHz-3GHz is used as the incident signal, and the comparison of $S_{11}$ and $S_{21}$ measured before and after compensation is shown in figure 5.

![S11 and S21 Comparison](image)

**Figure 5.** Comparison of $S_{11}$ and $S_{21}$ before and after parameter compensation.

In order to determine the location information of the soft fault and represent the reflection characteristics affected by the impedance mismatch intuitively, the reflected loss needs to be converted to the time-domain information to obtain the reflection coefficient by inverse Fourier transform. After processing, the reflection coefficient under this condition is shown in figure 6.

As can be seen from the figure 6, the reflection coefficient of the fault point before compensation is less than 0.02, which is no significantly different from the one at the non-fault part. However, after two compensations, the sudden changes of the reflection coefficient are obvious, which is easy to detect. The first two sudden changes of reflection coefficient are due to impedance mismatch between 50ohm and 75ohm. The last change is at the end of the cable, and the subsequent signal...
has no practical significance. Intuitively, the abscissa (times) of the three characteristic points are 95.38ns, 104.8ns, and 201.5ns, that is, the one-way transmission times of the signal on these three coaxial lines are 47.69ns, 4.71ns, and 48.35ns, and the ratio is 10.13: 1: 10.26. It can be considered approximately that the transmission speed of the signal on the cable remains unchanged, thus the length ratio of the three coaxial lines is 10.13: 1: 10.26, which is consistent with the structure of the coaxial-cable network established before. The transmission speed of the signal on the RG316 coaxial line is known to be $82.1 \times 10^8$ m/s, and then the periods of impedance changes obtained by theoretical calculation are 95.24ns, 104.76ns, and 200ns, respectively. The results show that the error of the actual measured result is less than 1% compared with the theoretical value, which can achieve the purpose of detecting soft faults accurately.

5. Conclusion
In this paper, considering the current situation of detection methods for the aviation bus, an improved detection method in frequency domain based on TDR and the double-coaxial mechanism are designed to diagnose the electrical faults of aviation buses with two typical structures. On this basis, by analyzing loss and compensation mechanism of the aeronautical bus, this paper studies a detection method of soft faults, and finally verifies the correctness of the algorithm through an example. The experimental results show that the scheme has both safety and accuracy for the detection of soft and hard faults for the aviation bus, which has certain engineering reference value.

6. References
[1] Zhang HT and Wang ZS 2012 Advance in fault diagnosis for aircraft electrical system Aeronautical Manufacturing Technology 20 60-69
[2] Huang W, Wang Z and Wang X 2017 Brief Introduction of 1553B Bus Technology and Its Application AER-Advances in Engineering Research vol 118, ed Liu H and Wan M pp 883-9
[3] Zhang JM, Wei J, Xie HB, Cao DS and Yao HY 2009 Detection and analysis of aerospace wire insulation faults based on TDR Acta Aeronautica et Astronautica Sinica 30(4) 706-12
[4] de Paulis F, Boudjefdjouf H, Bouchekara HREH, Orlandi A and Smail MK 2017 Performance improvements of wire fault diagnosis approach based on time-domain reflectometry IET Sci. Meas. Technol. 11(5) 538-44
[5] Wu SC 2011 An iterative inversion method for transmission line fault location Dissertations & Theses – Gradworks
[6] Wu S, Furse C and Lo C 2006 Noncontact probes for wire fault location with reflectometry IEEE Sensors Journal 6 1716-21
[7] Kafal M, Cozza A and Pichon L 2016 Locating multiple soft faults in wire networks using an alternative DORT implementation IEEE Trans. Instrum. Meas. 65(2) 399-406