Fault Detection of Aircraft Cable via Spread Spectrum Time Domain Reflectometry

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Abstract: As the airplane cable fault detection based on TDR (time domain reflectometry) is affected easily by various noise signals, which makes the reflected signal attenuate and distort heavily, failing to locate the fault. In order to solve these problems, a method of spread spectrum time domain reflectometry (SSTDR) is introduced in this paper, taking the advantage of the sharp peak of correlation function. The test signal is generated from ML sequence (MLS) modulated by sine wave in the same frequency. Theoretically, the test signal has the very high immunity of noise, which can be applied with excellent precision to fault location on the aircraft cable. In this paper, the method of SSTDR was normally simulated in MATLAB. Then, an experimental setup, based on LabVIEW, was organized to detect and locate the fault on the aircraft cable. It has been demonstrated that SSTDR has the high immunity of noise, reducing some detection errors effectively.

Keywords: SSTDR, Correlation function, Immunity of noise, Fault detection, LabVIEW.

1. Introduction

As is known, aircraft cable is playing a more and more important role in flight safety. With the long-term flight, the aircraft may suffer the problems of cable aging, and the aircraft cable problems have been considered to be the main cause of many disasters. What’s more, various of faults may occur to the aircraft cable because of the continuous shake and humid environment. While the plane is in flight, the cable failure is likely to result in catastrophic destruction to the aircraft. Thus, the detection and localization of faults with high accuracy is required strongly for diagnosis and maintenance of wiring systems.

Although the application of time domain Reflectometry (TDR) is utilized widely, there are still some problems, such as all kinds of noise signals, which will result in the superposition of a variety of signals including some noise signals, bringing the difficulty for the extraction of the reflected signal. Meanwhile, the degree of attenuation of the reference signal increases gradually with the increase of the propagation distance. Therefore, it is difficult to identify the reflected signal, resulting in great errors to the measurement results [1].
For the above reasons, an experimental setup, based on LabVIEW, was built up for the aircraft cable fault detection. The test signal, with high noise immunity of noise, has the sharp peak of correlation function, which makes it well suited to detect and locate some fault on the cable, reducing the detection errors greatly [2-4]. SSTDR can help maintenance personnel detect fault type and locate the fault on the cable quickly, and improve the detection efficiency for aircraft cable fault.

2. Principle Analysis

2.1. The Principle of Fault Detection

SSTDR is a method of fault detection based on spread spectrum technology [5]. The diagram of SSTDR cable fault detection is shown in Fig. 1. In this application, the MLS is modulated by sine wave in the same frequency, generating the test signal \( s(t) \) for SSTDR. The correlation between the incident and reflected signals identifies the type of fault and its location. In the beginning, the test system will send the signal \( s(t) \) onto one end of the cable, which will be reflected by some arbitrary number of impedance discontinuities on the cable. The reflected signal \( r(t) = a_s(t - t_f) \) will return to the test system after some transmission delay. Usually, along with the reflected signal will be some noise signals. Cross-correlate the total signals with the reference signal delayed by \( \tau \), and by changing the delay time \( \tau \), to make cross-correlator output maximum value. According to the feature of cross-correlation, at this point, there is \( \tau = t_f \), it is the reflection time corresponding to the cable fault point. If the velocity of the signal is known, multiply it with the time \( t_f \), the fault point can be obtained. What’s more, the system can tell the difference between the open-circuit fault and short-circuit fault by analyzing the peak of cross-correlation. When the second peak is right-side-up, the fault will be diagnosed with open-circuit fault. On the contrary, the second peak is inverted, then short-circuit fault will be confirmed [6].

\[
\text{Assume the velocity of the signal is constant in the cable, 0.7 times the speed of light. If the propagation delay } \tau \text{ of the reflected signal is got, the fault location } L \text{ can be obtained from the following formula [7]:} \\
L = \frac{1}{2} \times 0.7 \times c \times \tau , \tag{1}
\]

where \( c \) is the speed of light.

2.2. Design of Reference Signal

The optimal test signal depends on the nature of the application. For single cable, we select MLS, modulated by sinusoidal signal in the same frequency, as the test signal for SSTDR. The auto-correlation of MLS has obvious peak value and has the lowest side lobes, so the reflected signal can be identified easily. It is, therefore, optimal for detecting the fault of single cable.

\[
f(x) = c_0 + c_1x + c_2x^2 + \ldots + c_Nx^N = \sum_{j=0}^{N} c_jx^j \quad (c_0 = c_N = 1) \tag{2}
\]
N-linear shift register consists of $2^n - 1$ states, and the length of the sequence is $N = 2^n - 1$. The shift register is controlled by an external clock, in accordance with the clock shift output. As shown in Fig. 3(a) is the 31 bits of MLS simulation waveform.

In this paper, the test signal is generated from MLS modulated by sine wave in the same frequency. That is to say, sine wave remains primitive phase when the MLS appeared high, while inverted when low phase [8]. The simulation waveform of MLS, 31 bits, modulated by sine wave is shown in Fig. 4(a).

The modulated MLS help to improve the SNR (Signal Noise Ratio) of correlation, make the system identify the useful signal easier, and have the peak of correlation be more significant, improving the ability to resist the interference of noise. The 31 bit of MLS and its modulated waveform are separately simulated in Fig. 3(a) and Fig. 4(a), whose normalized auto-correlation waveform are shown in Fig. 3(b) and Fig. 4(b).

Correlation function algorithm is the core of the aircraft cable fault detection system, which reflects the dependency of the test signal and reflected signal. When the test signal and the reflected signal are identical in phase, a unique maximum will be output. Using correlation function, the system can identify the time difference between the test signal and the reflected signal, then the cable fault location can be obtained [9].

Since the reference signal is so low, the test signal, because of attenuation, becomes quite weak when it is reflected back again from the fault point. What’s worse, the reflected signal, usually interfered by some noise signals, will suffer serious deformation.

Through the correlation algorithm, the system can make the reflected signal, even if submerged in the
noise, be identified easier, improving the anti-interference ability of SSTDR.

Let \( r(t) \) be the received signal from the cable fault point, defined as follows:

\[
    r(t) = \sum_k a_k s(t - \tau_k) + n(t),
\]

where \( n(t) \) is the noise signal, \( a_k \) is the amplitude of reflected signal \( a_k s(t - \tau_k) \) relative to \( s(t) \) and \( \tau_k \) is the time delay before receiving reflection.

By shifting the reference signal \( s(t) \) with \( \tau \), cross-correlate it with the reflected signal, and the cross-correlation can be expressed as:

\[
    R_{ro}(\tau) = \int_0^T r(t) s(t - \tau) dt
\]

\[
    = \int_0^T \left( \sum_k a_k s(t - \tau_k) + n(t) \right) s(t - \tau) dt
\]

\[
    = \int_0^T s(t - \tau) \sum_k a_k s(t - \tau_k) dt + \int_0^T s(t - \tau) n(t) dt
\]

where \( T \) is the estimated time delay of the test signal.

The mathematic expectation value \( E(\cdot) \) of the cross-correlation \( R_{ro}(\tau) \) is considered as:

\[
    E[R_{ro}(\tau)] = E \left[ \int_0^T s(t - \tau) \sum_k a_k s(t - \tau_k) dt + \int_0^T s(t - \tau) n(t) dt \right]
\]

\[
    = \int_0^T s(t - \tau) \sum_k a_k s(t - \tau_k) dt
\]

Since the noise signal \( n(t) \)'s duration \( T_n >> T_s \), the reference signal \( s(t) \) and \( n(t) \) are asynchronous, that is, \( n(t) \) is statistically uncorrelated to \( s(t) \). So the correlation of \( s(t) \) and \( n(t) \) is nearly equal to zero and the formula (5) can be obtained. It can be concluded that although the reflected signal is the superposition of the injected signal and noise signal, however, \( s(t) \) and \( n(t) \) are not synchronous, so that the cross-correlation of them is zero. That is to say, the noise signal \( n(t) \) has nearly no effect on the cross-correlation of signal. It is also known that the cross-correlation of the reflected signal and reference signal, just when they are identical in phase, has only one peak. The local peak time of the cross-correlation function, \( \tau = T_l \), will be utilized to accurately measure the propagation delay of the reflected signal, which is then to be converted into the fault location with knowledge of the velocity of propagation [10]. In the mathematical theory, it has been proved that the correlation method has the strong ability to filter out the noise.

The SSTDR test signal, interfered by the white noise, and its normalized auto-correlation function simulation waveform are shown in Fig. 6.

\[\text{(a) SSTDR test signal interfered by white noise}\]

\[\text{(b) Normalized Auto-correlation of SSTDR signal interfered by white noise}\]

Fig. 6. SSTDR signal interfered by white noise and its normalized auto-correlation simulation waveform.

Because of the noise, the SSTDR test signal results in serious distortion, but its auto-correlation has still obviously sharp peak. That is to say, the noise has no effect on the result of auto-correlation. Theoretically, it proves the feasibility of the test signal with high immunity of noise signals in the detection of aircraft cable fault.

2.4. Technical Analysis

According to the correlation function theory, the test signal \( s(t) \), whose auto-correlation has a certain periodicity, when more than one cycle, there will be more than one auto-correlation peaks, which may be confused with the cross-correlation of the cable fault point, resulting in misjudgment. So the correlation must be completed in a cycle time. However, the fault location cannot be achieved if the fault point is too close to the test end, with the superposition the \( s(t) \) auto-correlation and the cross-correlation. So the range of the cable length, to be tested, must meet the following expression:

\[
    \frac{1}{2} \times T_s \times V \leq L \leq \frac{1}{2} \times N \times T_s \times V ,
\]

where \( V \) is the velocity of signal on the cable, about 0.7 times the speed of light; \( N \) is the length of MLS.

The following formulas can be got from (6):

The minimum detectable distance:

\[
    L_{\text{min}} = \frac{1}{2} \times T_s \times V ,
\]
And the maximum detectable distance:

\[ L_{\text{max}} = \frac{1}{2} \times N \times T_c \times V, \]  

(8)

When the velocity of propagation \( V \) is constant, the range resolution can be obtained:

\[ \Delta L = \frac{1}{2} |\tau - t_0| \times V, \]  

(9)

So, the resolution is considered to be closely related to the time delay \( \tau \).

3. Experimental Setup

3.1. Equipment Components

To demonstrate the ability of SSTDR to detect and locate short-circuit and open-circuit types of fault on aircraft cables, an experimental SSTDR system was organized as shown in Fig. 7. The system consists mainly of the PXI bus controller (computer for experimental SSTDR), arbitrary waveform generator, digital oscilloscope, and a “T” connector.

![Fig. 7. Experimental setup for SSTDR.](image)

To automatically control the instruments, the arbitrary waveform generator (utilized to generate some certain frequency of SSTDR test signal) and digital oscilloscope are connected to the PXI bus controller. The test signal is transmitted down the target cable via one port of the “T” connector. If there is a fault in the cable, because of the change of impedance, the test signal will be reflected to the digital oscilloscope via the other port of “T” connector. The computer controls and synchronizes the arbitrary waveform generator and digital oscilloscope, executes the cross-correlation of the reference signal and reflected signals, and obtains the round-trip propagation time to calculate the location of fault.

3.2. Algorithm Process

In the organization and management of the PXI bus controller, the test signal will be generated by the arbitrary waveform generator, then the computer complete the signal processing, along with the terminal display function. The main algorithm process chart is shown in Fig. 8.

![Fig. 8. Diagram for the main algorithm process.](image)

4. Result and Analysis

In order to verify the SSTDR simulation characteristics, the present experiments were conducted to detect short-circuit and open-circuit faults for different lengths of aircraft cable. Also note that the sampling rates for reflected signal acquisition of the SSTDR is 1 GHz. Let the incident signal chip rate is \( T_c = 1/30 \) MHz, and the amplitude of the incident signal is set to 1 V. The length of MLS is \( N=63 \). According to the expression (6), it can be known the range of the cable length which can be tested: \( 3.33 \text{ m} \leq L \leq 210 \text{ m} \). Because of the low amplitude, the maximum measurable length may not reach the theoretical results.

The reflected signal waveform for open-circuit fault of 35 m cable is shown in Fig. 9 (a). It can be known the reflection signal has some certain attenuation in the amplitude, with the time delay compared with the reference signal. Through
correlation algorithm, the normalized correlation waveform is obtained in Fig. 9 (b). The estimated time of the first peak, which is the reference signal itself, is 200 ns, while the estimated time of the second peak (cross-correlation of the reference signal and the reflected signal) is about 374.4 ns. With the signal velocity of propagation on the cable \( V = 2.10 \times 10^8 \text{ m/sec} \), the location of the fault can be estimated to be 34.88 m. While the second peak is right-side-up, so it is diagnosed with an open-circuit fault type.

![The reflected signal for open-circuit](image1)

![The Normalized Correlation for open-circuit](image2)

**Fig. 9.** The Reflected signal and Normalized Correlation waveform for open-circuit.

As shown in Fig. 10 (a) is the reflected signal of short-circuit fault, inverted in phase compared with Fig. 9(a). The second peak is also inverted in its normalized correlation shown in Fig. 10 (b).

![The reflected signal for short-circuit](image3)

![The Normalized Correlation for short-circuit](image4)

**Fig. 10.** The Reflected signal and Normalized Correlation waveform for short-circuit.

Afterwards, some different lengths of aircraft cables were selected for open-circuit and short-circuit faults test, and the test results are shown in Table 1.

For a more graphical comparison of the results, Table 2 lists the relative errors of the measurement results for different lengths of aircraft cables.

**Table 1.** Results of the cable location.

<table>
<thead>
<tr>
<th>Length</th>
<th>12 m</th>
<th>25 m</th>
<th>35 m</th>
<th>43 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-circuit Fault</td>
<td>11.92 m</td>
<td>24.90 m</td>
<td>34.88 m</td>
<td>42.85 m</td>
</tr>
<tr>
<td>Short-circuit Fault</td>
<td>11.88 m</td>
<td>24.94 m</td>
<td>34.90 m</td>
<td>42.86 m</td>
</tr>
</tbody>
</table>

**Table 2.** Relative Errors.

<table>
<thead>
<tr>
<th>Length</th>
<th>12 m</th>
<th>25 m</th>
<th>35 m</th>
<th>43 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-circuit Fault</td>
<td>1.00 %</td>
<td>0.60 %</td>
<td>0.46 %</td>
<td>0.44 %</td>
</tr>
<tr>
<td>Short-circuit Fault</td>
<td>1.17 %</td>
<td>0.64 %</td>
<td>0.54 %</td>
<td>0.49 %</td>
</tr>
</tbody>
</table>

From Table 1 and Table 2, it can be seen that SSTDR method has the good accuracy in locating the aircraft cable fault, showing its strong fault detection capability.

### 5. Conclusion

In this paper, short-circuit and open-circuit faults are detected accurately, using the method of spread spectrum time domain reflectometry. The MLS, modulated by the sine wave, with the characteristics of sharp correlation peak and high immunity of noise, was selected as test signal. The experimental results proved the feasibility of SSTDR for aircraft cable fault detection. Moreover, SSTDR will play the more and more part role in detecting faults in future, especially, aircraft cable fault detection on-line. The low test signal levels and high noise immunity of these test methods make them well suited to test for intermittent wiring failures such as open circuits, short circuits, and arcs on cables in aircraft in flight.
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