Design of Aircraft Wire Faults Detecting and Locating System based on DSP

Zhangang YANG, Chengzong LIU, Hongguang LI, Xudong SHI
Aeronautical automation college, Civil Aviation University of China, Tianjin, 300300, China
Tel.: +86-022-24092718
E-mail: zgyang@cauc.edu.cn

Received: 29 July 2013 / Accepted: 25 October 2013 / Published: 30 November 2013

Abstract: To enhance the aircraft wire detection rate of fault detecting and locating accuracy, a comprehensive portable test system for wire fault diagnosis using reflectometry was presented to detecting and locating fault location. The hardware system consists of DSP control core, pulse transmitter circuit, signal acquisition circuit and LCD circuit, and in this system, a pulse was launched and a reflected signal was received. After the threshold de-noising to the reflected signal based on wavelet decomposition, the exactly fault type and location of the wire was determined by least squares method. The experimental results indicate that this system can detect and locate the aircraft wire faults accurately.

Copyright © 2013 IFSA.

Keywords: Portable, DSP control core, Wire fault diagnosis, De-noising, Least squares method.

1. Introduction

Wiring is a critical system in aircraft, now electrical wiring and interconnected systems have become a major area of research and development for aircraft. Aircraft wiring integrity and safety related issues are known to be very serious and have received a great deal interest after several tragic mishaps and hundreds of thousands of lost mission hours [1]. Much of this wires is routed behind panels or wrapped in special protective jackets, and is not accessible even during heavy maintenance when most of the panels are removed. Also, the wire system replacement is very expensive, and a typical aircraft wire replacement will cost $1,000,000 to $5,000,000, the fault of the aircraft wire is always considered difficult to be detected. It is estimated that 1.8 million people was engaged in the maintenance of aircraft wire each year in the United States, so the choice of the fast and portable test instrument for aircraft wire fault detection is particularly necessary [2]. Therefore, this paper aims to design a DSP-based aircraft wire fault tester system. This system adopts the principle of time domain reflectometry, processes the reflected signal using wavelet noise reduction and the method of least squares, and gets the fault position and fault type. Eventually the result will display on the LCD screen. This system can help maintenance personnel find out the fault type and location quickly, and immediately improve the efficiency of aircraft maintenance personnel.

This paper is organized as follows: in Section II, modeling of the normal and faulty aircraft electric wire based on RLCG method is presented. Section III describes the hardware for detecting and locating system. The wavelet transform technology based fault signal noise reduction and the least squares method based fault location estimation is analyzed in Section IV, and experiment results are presented in Section V. The paper is concluded in Section VI.
2. Wire Fault Diagnose Principle

Aircraft electric power wire can be modeled as a transmission line with distributed resistance, inductance, shunt capacitance and shunt conductance [3]. An RLCG based wire model is developed in Fig. 1. Es and i represent the current and voltage that are measured. The R, L, C, G are the resistance, inductance, shunt capacitance and shunt conductance of the wire per meter length, respectively.

![An RLCG based wire model.](image)

The two-port electrical networks shown in Fig. 2 can be represented as follows:

\[
\begin{align*}
\frac{\partial}{\partial x} u(x,t) &= i(x,t) + L \frac{\partial}{\partial t} i(x,t) \\
\frac{\partial}{\partial t} i(x,t) &= u(x,t) + C \frac{\partial}{\partial t} u(x,t)
\end{align*}
\]

(1)

The formulae of electrical networks are expressed in complex form

\[
\begin{align*}
U(x) &= A_x e^{-j\alpha x} + A_e e^{j\alpha x} \\
I(x) &= \frac{1}{Z_0} (A_x e^{-j\alpha x} - A_e e^{j\alpha x})
\end{align*}
\]

(2)

where \( \alpha = \omega \sqrt{L/C} \), \( Z_0 = \sqrt{L/C} \).

Equations (2) can be rewritten as:

\[
\begin{align*}
U &= U_+ + U_- \\
I &= I_+ + I_-
\end{align*}
\]

(3)

where \( U_+ \) is the complex amplitude of injected signal, \( U_- \) the complex amplitude of reflected signal.

Where \( \frac{U_+}{I_+} = Z_0 \), \( \frac{U_-}{I_-} = -Z_0 \), the minus in the front imply there is an opposite direction between the real current and the reference current.

The reflection coefficient can be defined as

\[
\rho = \frac{U_-}{U_+} = \frac{I_-}{I_+}
\]

(4)

For the wire model in Fig. 1, there are several test technologies that can be used to pinpoint the location of wiring faults. Some of the most publicized methods are: time domain reflectometry (TDR) [4], frequency domain reflectometry (FDR) [5], pulse arrested spark discharge (PASD) [6], multi-carrier reflectometry (MCR) [7], spread spectrum time domain reflectometry (SSTDR) [8]. In this paper, the TDR principle of time domain reflectometry was used as the theoretical basis. If a high frequency signal was injected to the test wire, a reflected signal is received but there exist a delay time correlated to the fault type between the injected and reflected signals.

When the fault type is short circuit fault, the line impedance \( Z=0 \), and the reflection coefficient \( \rho = -1 \), the voltage at the fault point is given as

\[
U = U_+ + U_- = U_+ + \rho U_+ = 0
\]

When the fault type is open circuit fault, the line impedance \( Z=\infty \), and the reflection coefficient \( \rho = 1 \), the voltage at the fault point is given as

\[
U = U_+ + U_- = U_+ + \rho U_+ = 2U_+
\]

The voltage waveforms of short circuit and open circuit fault as shown in Fig. 2.

![The voltage waveforms of short circuit and open circuit fault.](image)

This method, with high accuracy, is mainly used to measure short-circuit fault and open fault. If the propagation velocity of the pulse in the wire is known, then the wire fault type and position can be achieved by measuring the delay time between the injected wave and the reflected wave. The formula is given as

\[
L = \frac{v \times t}{2} = \frac{c \times t}{2 \times \sqrt{\epsilon}}
\]

(5)
where \( v \) is the transmission speed of the electrical signal in the medium, \( t \) is the delay time between the injected pulse and the reflected pulse; \( L \) is the distance between the fault point and test point; \( c \) is the speed of light, about \( 3 \times 10^8 \) m/s; \( \varepsilon \) is the relative dielectric constant, which is changing with the transmission medium. When \( \varepsilon \) is smaller, the propagation velocity of the signal will be faster in the medium.

3. Hardware for Wire Fault Detecting and Locating System

The hardware system consists of DSP core, low-voltage narrow pulse transmitter circuit, high-speed A/D acquisition circuit, interface conversion circuit, small size LCD screen, a small keyboard and power supply system. The block diagram is shown in Fig. 3.

The method of fault information processing of this system will send pulse signals to the wire and collected the reflected signals by the AD, and select 2500 discrete points from collection points as the processed signal which contains fault feature of wire.

4. Software for Wire Fault Detecting and Locating System

4.1. General Overview of the Software Design

The main functions of the aircraft wire diagnose system software are: the launch of the low-voltage pulse signal, the acquisition of the reflected signal wire, fault location, data display and etc.

![Fig. 3. The comprehensive diagram of aircraft wire testing system.](image)

The software can be divided into: System initialization module, low-voltage pulse transmitter module, data acquisition module, data processing module and LCD module. The main program flow chart is shown on Fig. 4 (a).

![Fig. 4 (a) The main program flow chart of the testing system.](image)

![Fig. 4 (b). The entire workflow of the main program.](image)
4.2. Fault Signal Noise Reduction

The main difficulty influencing the diagnosis accuracy is to extract the fault feature of wire. Due to the existence of strong background noise, the signal of wire containing fault information is too weak to identify. At present, the wavelet analysis is widely used due to its good denoising and filtering characteristic [9, 10]. Different from other time frequency analysis technology, wavelet analysis has good localized capability in the time and frequency plane. Through wavelet transformation, the signal processing effect is similar to filtering through a band pass filter. As a result, the high frequency noise components, low frequency fault characteristic and resonance modulation components can be divided individually.

The wavelet noise reduction algorithms can be efficiently implemented in TMS320VC5509A. The TMS320VC5509A fixed-point digital signal processor (DSP) is based on the TMS320C55xDSP generation CPU processor core. The C55xDSP architecture achieves high performance and low power through increased parallelism and total focus on reduction in power dissipation, wavelet noise reduction algorithms can be efficiently implemented. The DSP-based wavelet noise reduction flow chart is shown in Fig. 5.

$$X_n = S_n + \sigma e_n, n = 0, 1, \ldots, N - 1,$$  \hspace{1cm} (6)

where $X_n$ is the signal containing noise, $S_n$ is the original signal, $e_n$ is the Gaussian white noise, and $\sigma$ is the deviation of the noise signal. Actually, the real signal $S_n$ which is described by the wavelet packet coefficients can be received from the noise signal $X_n$, and the wavelet packet coefficients is correlated to the signal energy, the coefficients is bigger, the energy is stronger. Also there are different characteristics in the relationship of wavelet transform coefficient and scale when the original signal and the random noise are transformed on the different scale, so the wavelet components which were dominated by the noise can be filtered and the wavelet components which were dominated by the original signal was retained, finally the original signal was acquired by wavelet reconstruction algorithm.

Suppose $f_j^+ (t) \in U_j^+$, then $f_j^+ (t)$ can be described in:

$$f_j^+ (t) = \sum_{i=0}^{2^j-1} d_i^+ 2^j U_i (2^j t - l)$$  \hspace{1cm} (7)

$f_j^+ (t)$ can be decomposed into $f_{j_{\text{lo}}}^+ (t)$ and $f_{j_{\text{hi}}}^+ (t)$, the formula is given as:

$$\begin{align*}
& c_{j_{\text{lo}}} = \sum h_{k_{\text{lo}}} c_{j_{\text{hi}}}^k, \\
& d_{j_{\text{lo}}} = \sum g_{k_{\text{lo}}} d_{j_{\text{hi}}}^k,
\end{align*}$$  \hspace{1cm} (8)

where $c$ is the low frequency component of the original signal, $h$ is the impulse response of $c$; $d$ is the high frequency component of the original signal, and $g$ is the impulse response of $c$. In this paper, db10 was selected as the wavelet basis function, so the wavelet coefficients corresponding to the high-pass filter is:

$$g[] = \begin{bmatrix} 0.3687144, 0.8129331, -0.1523958, -0.4512983, 0.0709618, 0.0338541 \end{bmatrix}$$

The wavelet coefficients corresponding to the low-pass filter is:

$$h[] = \begin{bmatrix} -0.4852975, 0.8166415, -0.4801027, -0.1545779, 0.0812496, 0.0382582 \end{bmatrix}$$

where $g$ and $h$ are the one dimensional array whose size is 6. The integer variable $m$ is defined as the wavelet coefficient, and the one dimensional array sca with single precision, whose length is $m+1$, was used to store the data length of each wavelet decomposition. The sampling length is 2048 in this paper, so $sca(0)=2048$, and $c[sca[k-1]]-c[sca[k]-1]$ is the $k$th layer low frequency smoothing signal after wavelet decomposition.

The 2048 original discrete data are stored in the $c[0]$-$c[2047]$. We can get the first set of data $c[2048]$ in the first layer of low-frequency signal by performing multiply-accumulate $c[0]$-$c[5]$ with the six coefficients of the scaling function $h$, and we get $c[2047]$ by performing multiply-accumulate $c[2]-c[7]$ with the six coefficients of the scaling function $g$. The DSP-based wavelet noise reduction flowchart is shown in Fig. 5.

Fig. 5. The wavelet denoising flowchart DSP-based.
function h. And so on we can get c[2046]–c[2045]…separately.

Since the length of the signal data of the low layer is always half of the upper layer, the first layer of low-frequency signal is stored in c[2048]–c[2048+1024] after data decomposition. Similarly, d is also the one-dimensional array of single-precision, so we can get d[2048]–d[2047]…separately. By the above method, we can knew that the first layer of high-frequency signal is stored in d[2048]–d[2048+1024]. The flow chart after wavelet decomposition and the threshold processing based on DSP is shown in Fig. 6.

Fig. 6. Flow chart of wavelet decomposition and the threshold processing.

The reconfigurable algorithm of \( f_{j+1}^{2n}(t) \), \( f_{j+1}^{2n+1}(t) \), \( f_j^i(t) \) is:

\[
d_i^{\alpha n} = \sum_k (h_{-2k} c_k^{i+1,2n} + g_{-2k} d_k^{i+1,2n})
\]  

(9)

Estimated wavelet coefficients can be obtained after the signal decomposition and each scale threshold quantization of the high-frequency coefficients. So we reconstruct the one-dimensional wavelet reconstruction of the underlying low-frequency coefficients of wavelet decomposition and layers of high-frequency coefficients. The flowchart of wavelet reconstruction based on DSP is shown Fig. 7.

Since signal sampling system is sensitive to environment change and the noise signal, the wavelet de-noising algorithm was applied to the sampling signal. The original signal waveform and the de-noising signal were shown in Fig. 8. It was obviously that there is random noise disturbance overlaying on the original signal.

Fig. 7. Wavelet reconstruction flowchart based on DSP.

### 4.3. Fault Position Information Processing

**Wire Faults Detecting and Locating**

After wavelet de-noising, the next step is to determine the fault type and position according to the type of the reflected waveform. In this paper, by using the moving least-squares method [11], the fitting curve and the extreme point of fitting curve was obtained.

In a subdomain of the fitting area, a fitting function \( f(x) \) can be given as:

\[
f(x) = \sum_{i=1}^{m} a_i(x) p_i(x) = p^T(x) a(x)
\]  

(10)
where $\alpha(x) = [\alpha_1(x), \alpha_2(x), \Lambda, \alpha_m(x)]^T$ is the coefficient to be solved, which is the function about $x$. And $p(x) = [p_1(x), p_2(x), \Lambda, p_m(x)]^T$ is the basis function of fitting function, which is a k-order perfect polynomial, and $m$ is the number of items of the base function.

We can calculate the moving least squares (MLS) fitting function:

$$f(x) = \sum_{i=1}^{n} \phi_i(x) y_i$$

(11)

where $\phi_i(x)$ is the shape function and $k$ is the order:

$$\phi_i(x) = [\phi_1^k(x), \phi_2^k(x), \Lambda, \phi_m^k(x)] = p^T(x)A^{-1}(x)B(x)$$

(12)

$$A(x) = \sum_{i=1}^{n} w(x-x_i) p(x_i) p^T(x_i)$$

(13)

$$B(x) = [w(x-x_1)p(x_1), w(x-x_2)p(x_2), \Lambda, w(x-x_m)p(x_m)]$$

(14)

$$y^T = [y_1, y_2, \Lambda, y_m]$$

(15)

When $k=0$, $p(x) = \{1\}$, whose shape function is:

$$\phi_{shaped}(x) = \frac{w(x-x_i)}{\sum_{i=1}^{n} w(x-x_i)}$$

(16)

Whether $p(x)$ is polynomial or not, it can be see $f(x)$, in formula (15), is not the polynomial. When $p \in C$, $w \in C^S$, fitting function $f \in C^{min(r,s)}$.

Moving least squares weighting function $w(x-x_i)$ is non-negative, monotone decreasing with $|x-x_i|$ increasing. We should choose smooth weight function, for this will affect the continuity of fitting function. In this paper, the spline function was chosen as the weight function, $s = x - x_i$, $\bar{s} = \frac{s}{s_{max}}$,

then cubic spline article weighting function can be given as formula (17):

$$w(\bar{s}) = \begin{cases} 
\frac{2}{3} - 4\bar{s}^2 + 4\bar{s}^3 (\bar{s} \leq \frac{1}{2}) \\
\frac{4}{3} - 4\bar{s}^2 - \frac{4}{3}\bar{s}^3 (\frac{1}{2} \leq \bar{s} \leq 1) \\
0 (\bar{s} > 1)
\end{cases}$$

(17)

To make $A(x)$ is reversible in formula (13), there will need enough nodes in the affected area. When the base function using in formula (10) is a linear basis function, two non-overlapping nodes at least should be included in the affected area of curve fitting. And in surface fitting, three nodes, not in the same straight line, should be included in the affected area at least.

The moving least squares used to curve fitting includes the following steps: gridding the fitting area first, then calculating node values on the grid points according to formula (15), connecting each grid node together at last, and getting the fitting curve.

By moving least squares, the 2500 discrete can be described by fitted curve, and the extreme points A, B, C, and D can be obtained by derivative the fitting curve synthesis repeatedly.

In accordance with the time value of the extreme points, we can calculate the difference time between the incident wave and the reflected wave, and get the fault position information according to the difference time. A typical wire fault waveform is shown in Fig. 9.

Time difference can be drawn based on the four points identified:

$$\Delta t = \left| \frac{t_o - t_i}{2} - \frac{t_s - t_i}{2} \right|$$

(18)

Then the fault position can be calculated by formula (5).
5. Experiments and Results Analysis

Under laboratory conditions, we tested the 5 m, 15 m, 50 m wire, the waveform is shown in Fig. 10, Fig. 11, Fig. 12 respectively. The tested data of 10 groups is shown in Table 1. Experiment results indicate that max measuring error of 5 m, 15 m, 50 m by using the aircraft wire faults detecting and locating system is 3.00 %, 1.67 %, 1.54 % respectively.

<table>
<thead>
<tr>
<th>Actual location (m)</th>
<th>Short circuit fault ten times measuring location (m)</th>
<th>Open circuit fault ten times measuring location (m)</th>
<th>Max measurement error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5.06 4.93 4.97 5.15 5.01 5.02 4.86 5.12 4.99 5</td>
<td>5.04 4.97 4.98 5.02 5.05 5.04 4.97 4.98 5.05 5.05</td>
<td>3.00 % (short) 2.80 % (open)</td>
</tr>
<tr>
<td>15</td>
<td>15.25 14.89 15.03 14.83 14.76 14.97 15.08 15.06 14.82 15.02</td>
<td>14.99 15.11 14.95 15.02 15.19 14.89 15.14 14.23 15.17 14.98</td>
<td>1.53 % (short) 1.67 % (open)</td>
</tr>
<tr>
<td>50</td>
<td>50.14 49.99 50.14 49.87 49.32 49.23 50.32 50.1 49.92 49.86</td>
<td>50.65 49.88 50.26 49.27 50.03 50.11 50.07 50.31 49.68 50.12</td>
<td>1.30 % (short) 1.54 % (open)</td>
</tr>
</tbody>
</table>
6. Conclusion

In this paper, a DSP-based aircraft wire fault tester system was introduced. First, the test system is designed to be portable, to avoid disadvantage of the bulky and not easy to carry, which gives the aircraft testing and maintenance of a great deal of convenience. Second, the tester system is less power consumption, and energy saving without the need for an external power supply. Also the tester is high degree of intelligence system, and the step for the detection process is relatively simple, which greatly improves the efficiency and accuracy of the wire maintenance.

Acknowledgements

This paper was supported by the National Nature Science Foundation of China (51277011), the Tianjin Key Technology R&D Program (11ZCKFGX04000), The Fundamental Research Funds for The Central Universities (ZXH2012C006; ZXH2012B002 & 3122013P005).

References