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Research on Aircraft Cable Defects Locating Method Based on Time-Frequency Domain Reflection

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Abstract

This paper presents an aircraft cable fault detection and location method based on TFDR in order to detect the intermittent faults effectively and to cope with the serial and after-connector faults being difficult to be detected in time domain reflection. In this method, the correlation function of reflected and reference signal is utilized to detect and locate the aircraft fault according to the characteristics of reflected and reference signal in time-frequency domain, so the hit rate of detecting and locating intermittent faults can be improved effectively. In the work process, the reflected signal is interfered by the noise and false alarm takes place frequently, so the threshold de-noising method based on wavelet decomposition is utilized to decrease the noise interference and reduce the fault alarm rate. Then the time-frequency cross correlation function of the reference signal and the reflected signal based on Wigner-Ville distribution is computed in order to locate the fault position. At last, LabVIEW is applied to implement operation and control interface, the main function of which is to link and control MATLAB and LABSQL. Utilizing the strong calculating capability and the abundant function library of MATLAB, the signal processing turn to be easily realized, moreover LabVIEW help the system to be more reliable and updated easily.

Keywords: Airworthiness; Aircraft cable; Fault location; TFDR; Virtual instrument technology

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1. Introduction

Aircraft cable is an important device that transports powers and signals for aircraft electrical systems. According to airworthiness standards of the General Administration of Civil Aviation of China (CCAR-25-R3), the development of the aviation cable is light weight, small diameter, withstanding high temperature and high reliability. Absolutely not allowed short, open and fray fault. Once the aircraft cable got broken, the ability of the aircraft airworthiness could be affected seriously, especially the continuity of the cable. All of the damages, such as friction with the air splint, oil leak and high temperature can cause the problem of the cable. So in order to ensure the high ability of the aircraft airworthiness, the research on efficient aircraft cable defects locating method is very necessary.

Lots of problems, such as unstable indicating instruments, abnormal signals, as well as operating failures, can be leaded by aircraft cable fault that directly threats flight security. While the structure of the aircraft is compact, most of the cables are fixed in narrow special. In this case, lots of the cable faults are difficult to be detected and located. Therefore, not only does cable fault bring security threat to aircraft, but also has seriously effect on maintenance efficiency and maintenance cost [1].

The intermittent fault, serial faults and after-connector faults of aircraft cable are difficult to be located because of the serious decay in the time domain reflectometry (TDR). In addition, the fault point is located by the rising and falling edges of reflected signal and reference signal, the location accuracy is not accuracy enough because of the signal rising and falling time width [2].

The aim of this paper is to present and evaluate a method based on Time-Frequency domain reflection (TFDR) of fault location of aircraft cable [3]. On the base of the electromagnetic wave propagation and the cable characteristic impedance changing in the fault region, a serial process is designed. Firstly, a chirp signal multiplied by Gaussian envelope as reference signal is designed and emitted along the cable. Then, the time-frequency cross correlation function of the reference signal and the reflected signal based on Wigner-Ville distribution is computed. Secondly, in order to improve the accuracy of the location, wavelet decomposition de-noising algorithm is used to process the reflected signal and decrease the noise interference. The fault can be located accuracy according to the time-frequency cross correlation function of the reference signal and the reflected signal. Finally, LabVIEW is applied to implement operation and control interface, the main function of which is to link and control MATLAB and LABSQL. Utilizing the strong calculating capability and the abundant function library of MATLAB, the defects location turn to be easily realized.

2. Fault Location Principle

A linearly modulated chirp signal multiplied by a Gaussian envelope in the time domain to provide time localization is designed as the reference signal which mathematical expression is shown as Eq. (1).

$$s(t) = (\alpha / \pi)^{1/4} e^{-\alpha(t-t_0)^2/2 + j\beta(t-t_0)^2/2 + j\omega_0(t-t_0)} \tag{1}$$

Where α, β, t_0 and ω_0, whose are selected by the attenuation characteristics of the cables determine the time duration, frequency sweep rate, time center and frequency center, respectively. The Gaussian envelope localizes the reference signal in the time and frequency domain while the instantaneous frequency of the signal increases with time in a linear manner as depicted in Fig 1 [4, 5].

It is important to choose the four parameters of the reference signal. The next step is to design the parameters fitted for the experiments. For this signal, the estimated time Centre (t_s) and the time width (T_s) are shown as Eq. (2) and Eq. (3).

$$t_s = \int t\left|s(t)\right|^2 dt = t_0 \tag{2}$$

$$T_s^2 = \int (t-t_s)^2 \left|s(t)\right|^2 dt = 1/2\alpha \tag{3}$$

Take $t_0 = 0$ for convenience of calculation.

Get the Fourier transform of the chirp signal in Eq. (4).

$$S(\omega) = \sqrt{\sqrt{\alpha} / \sqrt{\pi}(\alpha - j\beta)} e^{-(\omega-\omega_0)^2/2(\alpha-j\beta)} \tag{4}$$

The center frequency (ω_s) and bandwidth (B_s) can be estimated in terms of $S(\omega)$ as Eq. (5) and Eq. (6).

$$\omega_s = \int \omega \left|s(\omega)\right|^2 d\omega = \omega_0 \tag{5}$$

$$B_s^2 = \int (\omega - \omega_s)^2 \left| s(\omega) \right|^2 d\omega = \tfrac{\alpha^2+\beta^2}{2\alpha} \tag{6}$$

However, the parameters are also selected by the characteristics of the cables and conditions.

The Wigner-Ville time-frequency distribution can be obtained in Eq. (7).

$$W(t,\omega) = \tfrac{1}{2\pi} \int s^*(t - \tfrac{1}{2}\tau) s(t + \tfrac{1}{2}\tau) e^{-j\tau\omega} d\tau \tag{7}$$

Then the Wigner-Ville distribution of the reference signal is shown in Eq. (8).

$$W_s(t,\omega) = \tfrac{1}{\pi} e^{-\alpha(t-t_0)^2 - (\omega - \beta(t-t_0) - \omega_0)^2/\alpha} \tag{8}$$

The time-frequency distributions of the superimposed signal which come from the reference signal and the reflected signals are calculated. Then these two time-frequency distributions are cross-correlated in the time-frequency domain. The peak in the time-frequency cross correlation function allows one to estimate an accurate round-trip propagation time and distance. Cross-correlation function is shown as follows.

$$C_{sr}(t) = \frac{2\pi}{E_s E_r} \iint W_r(t',\omega) W_s(t'-t,\omega) d\omega dt' \tag{9}$$

Where, W_r and W_S are time-frequency distributions of reference signal and reflected signals, respectively, which are calculated by Wigner-Ville transform. E_r and E_s are normalized coefficients. At last, the peak in the time-frequency cross correlation function allows one to estimate an accurate round-trip propagation time and distance.

The reference signal is emitted and it will propagate along the cable. When the cable fault take place, the characteristic impedance of coaxial cable will change and the reference signal will reflect and transmit at that place, thus the fault can be detected and located by the reflection phenomena, which is shown in Fig 2.

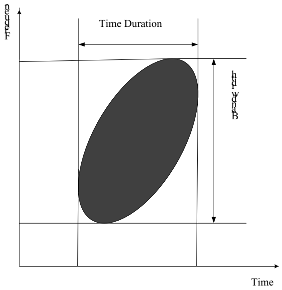

Fig. 1. Time-frequency domain reference signal

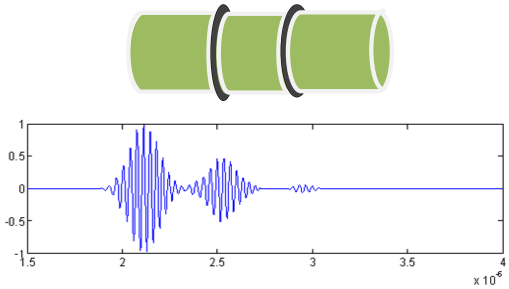

Fig. 2. The reference signal came across the changed impedance

3. Reflected Signal De-noising

Noise signal is amplified with the weak reflected signal's amplification. The wavelet threshold shrinkage algorithm is used to deduce the noise interference. Wavelet Analysis is a Multi-resolution analysis [6, 7]. The reflected signals can be decomposed in difference frequency parts accord its character, and the noise can be removed. Then reconstruct basic wavelet, the affected reflected signal can be modified.

For one-dimensional signal, the high frequency part impact 1st level data of the wavelet decomposition, low frequency part impact the deepest level of the wavelet decomposition. For the additive white noise, the amplitude of high frequency coefficients rapidly decay with the decomposition level's augment. The detection signal is a band-limited signal, and the wavelet coefficients concentrated in a band, but wavelet coefficients of noise throughout the frequency domain.

Wavelet decomposition have many characteristics such as time displacement character, expansion elasticity, so the interest coefficients exists only in reference signal and reflected signal window, outside of which is a noise signal.

The continuous wavelet transform of signal is defined as Eq. (10).

$$Wf(s,x)=\int_{-\infty}^{\infty} f(t)\cdot\frac{1}{\sqrt{s}}\psi^{*}(\frac{t-x}{s}\psi)dt=<f,\psi_{s,x}> \qquad (10)$$

Wavelet reconstruction algorithm is shown as Eq. (11).

$$S^{j-1}f(t)=\sum_{m}\overline{h}_{m}S^{j}f(t-2^{j}m)+\sum_{m}\overline{g}_{m}S^{j-1}f(t-2^{j}m) \qquad (11)$$

To achieve good noise reduction effect, the threshold should be selected just larger than the maximum noise level. Mini-maxi principle is a fixed threshold selection form, can get a minimum mean square deviation extreme. Because the noise reduction signal is similar to the estimation of the unknown regressive function estimation, such a threshold filter minimizes error in a given function's maximum mean square deviation. Mini-maxi threshold is defined as Eq. (12).

$$thr = \left(0.3936 + 0.1829 \cdot \left(\log(n)/\log(2)\right)\right) \cdot \sigma \tag{12}$$

Where n is the number of the wavelet coefficient.

The soft threshold is chosen as the coefficient adjustment method, which can be expressed as Eq. (13).

$$w_k^j = \begin{cases} sign(w_k^j) \times (c + \frac{1}{2}c), w_k^j > thr \\ 0, others \end{cases} \tag{13}$$

Where, $c = \left|w_k^j\right| - thr$

Noise signal in testing environment will disturb the reflected signals, which make it difficult to accurately identify. Comparison between non-denoised and denoised is shown in Fig 3.

4. Experiment System Design

4.1. Design of hardware

A ZT530 high-performance PCI signal generator made in ZTEC is utilized as a signal generator which gener-ates the Gaussian envelope Chirp signal with duration 50ns and amplitude 1V. A ZT450 PCI high speed data acquisition card is used as a signal acquisition, whose sampling frequency is 1GS/s. Portable industrial control computer produced by Advantech Company is used as main controller. MATLAB is used to deal with time-frequency correlation function and LabVIEW is utilized as the software platform. SFF-50-1 type coaxial cable is treated as the experiment object. TFDR aircraft cable fault location system is shown in Fig. 4 which block diagram is shown the in Fig. 5.

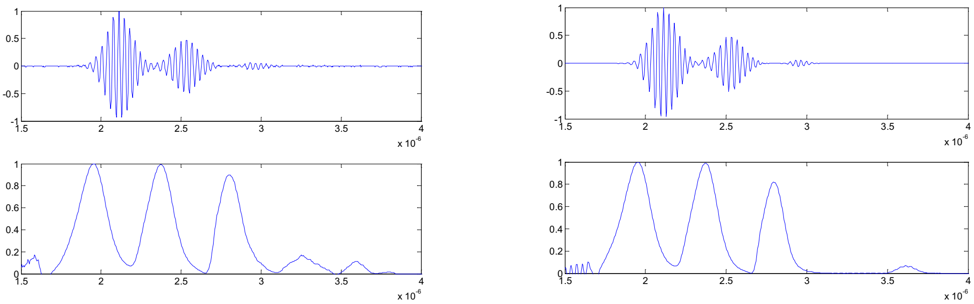

Fig. 3. (a) Result of non-denoising; (b) Result of denoising

Fig. 4. Location system

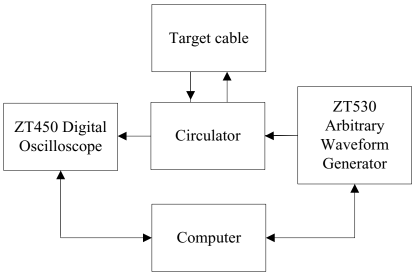

Fig. 5. Block diagram of system structure

4.2. Design of software

1) Reference signal generation

The pre-designed reference signal can be produced by importing .csv format file which is generated in the MATLAB into the soft-panel of the ZTEC signal generator. The reference signal is shown in Fig 6.

2) Detected signal acquisition

Data acquisition is closely related to DAC (Digital Analog Converter). Data acquisition is closely related to DAC (Digital Analog Converter). The basic mission of DAC is the physical signal extraction and measurement. In this paper, Date acquisition module is used to control the whole data acquisition system, including parameter configuration, state switch, result output, etc.

3) Detected signal processing

The MATLAB Script node of LabVIEW is used to execute wavelet threshold denoising and time-frequency correlation function processing in this paper. The block diagram of detected signal processing is shown in Fig 7.

Staff efficiency is a much important factor requested in “Airworthiness of aircraft” which is the eighth Annex to the Convention on International Civil Aviation. Therefore, intelligent detection of fault locations is particularly necessary. Intelligent fault diagnosis can be achieved by automatically determining the extreme points of time-frequency cross correlation function, in later sections, the local peak time of the time-frequency cross correlation function 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. The block diagram of locating the extreme points is shown in Fig 8.

4) The test result

This system can achieve signal acquisition, signal processing and test results storage. System front panel is shown as in Fig 9. The upper part of the interface shows collected time-domain signal, the lower part shows the test waveform after denoising and related treatment. Through the time-frequency domain correlation processing, reflection waveform has been amplified. Thus, the fault point can be located intelligently and easily.

Aircraft cable fault hit rates result of TDR and TFDR is shown in Table 1. With the increase in the number of fault points, the signal noise ratio becomes lower. When it arrives to a certain number, the signal energy attenuation to the classification of the noise, then the effect from noise is more serious. The ratio of the number of false alarm and the total number are shown in Table 2. As shown in Table 2, the number of fault false alarm rate increases with the number of faults. Consistent with the previous analysis, noise reduction by wavelet largely reduce the noise impact on the faults detection accuracy.

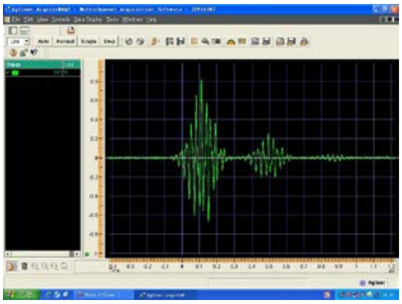

Fig. 6. Reference signal

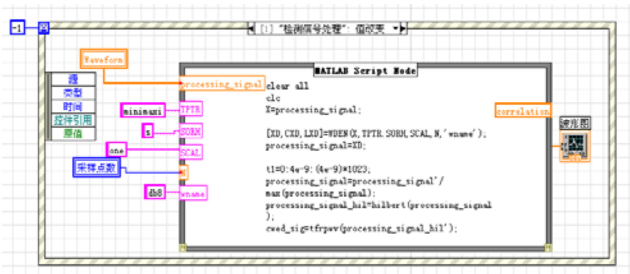

Fig. 7. Block diagram of detected signal processing

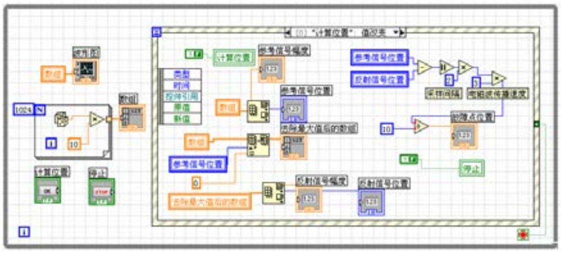

Fig. 8. Block diagram of locating the extreme points

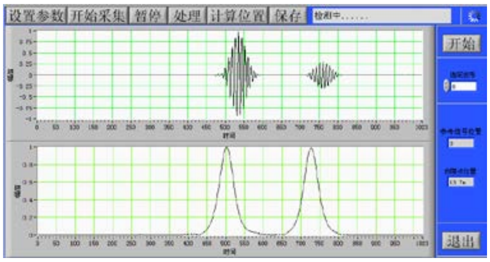

Fig. 9. System front panel

Table 1. Aircraft cable fault hit rates of TDR and TFDR

Faults number	TDR hite rate	TFDR hit rate
1	100%	100%
2	83%	100%
3	7%	53%
4	0	3%

Table 2. Analysis of aircraft cable fault false alarm rates

Fault number	Non-de-noising Fault false alarm rate	De-noising Fault false alarm rate
1	9%	0%
2	67%	5%
3	92%	22%
4	100%	84%

5. Conclusion

A robust method for aircraft cable fault detection and location based on the TFDR is presented which can solve the problems such as intermittent fault. Serial fault and after-connector fault are difficult to detected and located in TDR. A reference signal is designed which has a high resolution in both in time domain and frequency domain according to its characteristics of aircraft cable. A correlation function of reference signal and reflected signal based Wigner-Ville distribution is used to detect and locate the faults, so the hit rate can be improved. A threshold de-noising method based on wavelet decomposition is utilized to decrease the noise interference and reduce the fault alarm rate. The instrument is developed and the feasibility is verified by experiments. With these ways, the ability of the aircraft airworthiness can be improved effectively.

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