A Temperature Sensor Failure Diagnosis Approach in Frequency

Xiaojia Han
Laboratory of Industrial Control Network and System
Shenyang Institute of Automation, Chinese Academy of Sciences
Shenyang, China
University of Chinese Academy of Sciences
Beijing, China
E-mail: hanxiaojia@sia.cn

Aidong Xu, Bingjun Yan
Laboratory of Industrial Control Network and System
Shenyang Institute of Automation, Chinese Academy of Sciences
Shenyang, China

Jin Jiang
Department of Electrical and Computer Engineering
University of Western Ontario
London, Ontario, Canada

Chao Pei
Laboratory of Industrial Control Network and System
Shenyang Institute of Automation, Chinese Academy of Sciences
Shenyang, China
University of Chinese Academy of Sciences
Beijing, China

Abstract—This paper introduces an on-line diagnostic function for temperature sensors using a noise analysis approach. The deviation of temperature measurements from their average value is treated as the noise input data, then the noise data is filtered through the Butterworth filter. The power spectrum density estimation of the noise data is obtained by using the Welch method. The first-order characteristic of the temperature sensor is used to obtain the characteristic frequency of the sensor, which can then be used to determine the working status of the sensor. Finally, through a large number of experiments, the results have shown that the sensor's characteristic frequency in a failure condition is significantly higher than that in the normal state. So it verifies the feasibility of on-line diagnosis by using the noise analysis approach for the temperature sensor.

Keywords—temperature transmitter; temperature sensor; failure diagnosis; characteristic frequency

I. INTRODUCTION

In an industrial environment, the working state of a sensor directly affects the overall safety and performance of the system. A research report from the Center for Intelligent Maintenance System, in the United States, indicates that: more than 40% of alarm in a general automation system is false alarm, due to malfunction of the sensor itself [1]. Therefore, accuracy of sensor failure diagnosis is very important. Traditional sensor failure diagnosis methods are characterized by the following features: offline, periodicity. Between two consequent inspections, sensors may fail, it can lead to serious security risks [2]. In 1960s, the United States first began to investigate on failure diagnosis based on noise and vibration. In 1967, Machinery Failure Prevention Group was established under the guide of NASA [3]. Because the considerable economic benefit was brought by the diagnosis technology, the failure diagnosis of equipment had become a subject of focused research and later on extensive industrial applications. Diagnosis technologies have developed rapidly. Subsequently, the United Kingdom also started the research of the failure diagnosis. Machinery Health Center was established in the United Kingdom. The research and technological development in the field of failure diagnosis in China started relatively late, and it didn't attract deserved attention until 1985 [3].

Using the redundant information of sensor to perform diagnostic function is the basis for any sensor failure diagnosis. Different diagnostic methods have been developed for different types of redundant information. Such as, hardware redundancy, analytic redundancy and temporal redundancy [1]. Noise analysis method belongs to the temporal redundancy. Hardware redundancy requires multiple physical sensors. Its disadvantages are high cost, increased maintenance and occupation of space etc. Analytic redundancy needs reliable and accurate models. Noise analysis does not have the above limitations.

In a dynamic system, the time constant T in a first order system can reflect the inertia characteristics of the system. Whenever the inertia of the first-order system decreases, the process speed of response is becoming faster. On the contrary, the larger the inertia, the slower the response [4]. In this paper, time constant T is referred to as the response time. For a given temperature measurement system, the response time typically is constant, whether the input signal is first-order signal, ramp
signal or noise signal [3]. Since frequency analysis can carry a lot of information about the time domain characteristics, the characteristic frequency in frequency domain is used to diagnose the failure of a temperature sensor. Because the characteristic frequency and the response time are reciprocal relations, the health of the temperature sensor can be judged indirectly through the characteristics in the frequency domain.

In the paper, failure diagnosis algorithm for a temperature sensor has been developed in Section II. Description of testbed construction is given in Section III. Finally, a temperature sensor, Pt100 is selected as the experimental object. It has been demonstrated by experiments that a loose connection in a thermowell (the failure mode of the temperature sensor) can be correctly diagnosed by the noise analysis approach.

II. DESIGN OF A FAILURE DIAGNOSIS ALGORITHM FOR TEMPERATURE SENSORS

Using the frequency domain analysis technique to interpret the internal characteristics of a signal is the core of failure diagnosis algorithm for temperature sensor. The characteristic frequency is identified by using the fast Fourier transform (FFT) [5]. In practice, the Fourier transform is usually used to obtain the frequency characteristic information of the machine vibration signal. The traditional noise analysis approach for failure diagnosis is used in the internal combustion engine [6], motor [7], gearbox [8]. However, to the best of our knowledge, it has not been applied to the temperature sensor.

A temperature sensor Pt100 is used in this paper for demonstrating the design and test of the proposed algorithm. The specific process is described as follows: the deviations of the measurements from their average value is treated as noise input data, the noise data is filtered through the Butterworth filter. The power spectrum density estimation of the noise data is obtained by using the Welch method. The spectrum analysis of the noise data is mainly used to analyze the frequency components of the noise. When the temperature sensor is working properly, it can calculate the normal characteristic frequency. When a failure occurs in the sensor, the characteristic frequency will change [9]. The process of diagnosis algorithm can be shown in Fig. 1.

A. Butterworth Low Pass Digital Filter

A filter is a frequency selection device, which can be realized by hardware or software [10]. Butterworth filter is selected as a low-pass filter herein, the relationship of the input and output in time domain for the filter can be shown as follows in a form of convolution:

$$y(n) = x(n) * h(n)$$  \hspace{1cm} (1)

The corresponding relationship between the input and the output in frequency domain becomes (2):

$$Y(\Omega) = X(\Omega)H(\Omega)$$  \hspace{1cm} (2)

B. Welch Method of Power Spectrum Density Estimation

Welch algorithm is a modified algorithm of the cycle graph, which is proposed by Welch [11]. It is also an effective algorithm in the classical spectral estimation. The flow chart of power spectrum density estimation calculation is shown in Fig. 2.

Spectrum estimation in Welch method uses data segmentation and method of calculating the average after adding windows processing [12]. First, the noise data $x(n)$ is divided into the $K$ segments (where $N$ is the total number of data, $L$ is the number of each small data, $M$ is the integer power of 2). There is a data overlap between adjacent segments. In order to facilitate the calculation, when the value of $L$ is less than an integer power of 2, $L$ is set to 0 to make the length of $M$. Next, each will add a Hamming window function $w(n)$ to reduce the leakage of energy spectrum. Each windowed data segment is then used by FFT to achieve the power spectrum density estimation (which $U$ is the normalization factor, which is used to ensure the asymptotic unbiased estimation of spectrum). Finally, the average value of the power spectrum density estimation can be obtained.

Through this process, the magnitude of the estimation of the power spectrum density can be obtained. The frequency $f$ is expressed as follows:

$$f = \frac{n}{N_{FFT}} \times F_s \quad n \in \left[1, \frac{N_{FFT}}{2}\right]$$  \hspace{1cm} (3)

Wherein $N_{FFT}$ is the number of points for the FFT calculation, $F_s$ is the sampling frequency.
In practice, typically, the more data points \( N_{FFT} \), the better the results would be expected. However, in an actual implementation in an embedded environment, the size of the storage for the collected data is a primary consideration. In the current application, the total memory storage is about 7.00 kB. Through experimental verification and data compression, the amount of data chosen for this investigation is 1024.

III. DEVELOPMENT OF FAILURE DIAGNOSIS TEST PLATFORM

A. Hardware Test Platform

Temperature transmitter is selected as the experimental platform, which can be used to collect the temperature readings. After pre-processing, the temperature data are converted to a fieldbus data format to achieve temperature measurement function. The temperature transmitter is mainly composed of five components (shown in Fig. 3). Wherein, the port card is an interface connecting to the fieldbus, temperature sensors and isolation card. While using the temperature sensor, the data acquisition card can convert the temperature signal into analog voltage signal, then the analog voltage signal is converted into digital signal in ADC, so the transmitter can realize the function of temperature data acquisition. The communication card provides communication, control, failure diagnosis and maintenance functions about the fieldbus. The isolation card is mainly used to realize the isolation of the communication card and the acquisition card, which comprises power source isolation and signal isolation. Display card is used to provide the display function of temperature and other function block parameters.

The system core of the acquisition card is MSP. Communication card is not only the core component of temperature transmitter, but also the processor on which the failure diagnosis algorithms are being executed. The kernel of the communication card is ARM. The communication card is used to process the data transmitted by the acquisition card, run Profibus-PA protocol stack, and control the LCD display. This CPU can support external expansion to meet the data storage and computing needs of failure diagnosis algorithms.

B. Software Test Platform

MULTI (Green Hills Software) is selected as the embedded development environment. Nucleus PLUS is selected as the operating system. The operating system can meet the real time requirements, task pre-emption and multi-tasking kernel. In the software development environment, the real-time operating system Nucleus PLUS is transplanted to the communication card, and then different priorities for different tasks is complied. According to pre-emptive schedule, a round robin scheduling method is used in the same priority tasks. The task priority of the failure diagnosis algorithm is set to be 12. Memory pool for each task is established in the communication card.

When the temperature transmitter starts to operate, the clock, timer, ADC, USART, I/O and other parts are initialized by the acquisition card. Under the control of the CPU on the acquisition card, the calibration parameters are read by the acquisition card. Then through the read_data () function, the acquisition card can acquire the temperature sensor values and calculate the temperature values. Finally, the acquisition card sends the data to the communication card through a serial port. The flow chart of the data acquisition is shown in Fig. 4. The communication card receives the acquired data, and the data is injected into the memory pool. When the upper limit of the memory stack is reached, the diagnosis algorithm is performed. Otherwise, the acquisition process continues. The temperature sensor data processing flow chart is shown in Fig. 4 (b).

IV. EXPERIMENTAL PROCEDURE AND ANALYSIS OF RESULTS

The failure mode (without thermowell) of the temperature sensor is simulated. The measured room temperature is 22°C, the temperature sensor (in the normal mode) is put into the boiling hot water (at the boiling state) in the experiment. Under the same experimental condition, the thermowell of temperature sensor is removed, temperature sensor is put into the boiling hot water directly in the comparative experiment. The experimental platform is shown in Fig. 5. Pt100 is on the
left side. The temperature transmitter is in the middle. The voltage source is on the right side of Fig. 5.

![Experimental test platform](image)

Figure 5. Experimental test platform.

The experimental results are shown in Fig. 6. When the black power spectrum density estimation curve drops 20 dB in the normal mode, the abscissa value of the black curve is 2.07, the corresponding characteristic frequency is 7.91 Hz. When the red power spectrum density estimation curve drops 20 dB in failure mode, the abscissa value of the red curve is 2.90, as shown in Table I. The characteristic frequency is 18.16 Hz.

![Power spectrum densities for normal and failed sensors](image)

Figure 6. Power spectrum densities for normal and failed sensors.

It can be concluded that the characteristic frequency of the temperature sensor in failure mode is higher than that in the normal mode. Characteristic frequency is corresponding to the response time in the time domain. Therefore, it can be proved that the response time of the sensor in failure mode is shorter than that in the normal mode. Hence, the approach can determine whether the thermowell in the temperature sensor has dropped off.

V. CONCLUSION

The novelty of this paper is that the noise analysis approach is introduced to industrial sensors, which can determine the health of a temperature sensor by the sensor characteristic frequencies. The paper has demonstrated by analysis and also experiments that noise analysis in frequency domain can indeed distinguish whether a thermowell has come off from the sensor element.

| Operating mode | Parameter | Ordinate (dB) | Abscissa | Characteristic frequency (Hz) |
|----------------|-----------|---------------|----------|-----------------------------|
| Normal mode    | Ordinate (dB) | -16.95       | 2.07     | 7.91                        |
| Failure Mode   | Abscissa  | 2.90          | 18.16    |                             |

REFERENCES

[1] Y.L. Zhang, W.M. Chen, P. Zhang, S.R. Hu, X.W. Huang and W. Zheng, “An overview of sensor failure diagnosis techniques,” Sensor and microsystem, vol. 28 (1), pp. 4-6, 2009.
[2] Y.F. Liu and A.D. Xu, “Based on noise analysis of temperature sensor failure diagnosis technology,” Manufacturing industry automation, vol. 36 (12), pp. 20-22, 2014.
[3] Y.F. Liu, “Research and development of sensor failure diagnosis technology based on noise analysis,” Master Thesis, Shenyang: Shenyang Institute of automation, Chinese Academy of Sciences, 2015.
[4] S.S. Hu, The principle of automatic control, Beijing: Science Press, 2007.
[5] H.M. Hashemian, “On-line monitoring applications in nuclear power plants,” Progress in Nuclear Energy, vol. 53(2), pp. 167-181, 2011.
[6] C. Lv and G.Z. Wang, “Noise diagnosis based on time frequency domain model,” Vibration and shock, vol. 24 (2), pp. 54-57, 2005.
[7] G.R. Liang, “Research on failure diagnosis of motor based on noise source,” Master Thesis, Guangzhou: Guangdong University of Technology, 2013.
[8] X.J. Lu and C. Wei, “Spectral analysis and failure diagnosis of gearbox noise,” Vibration and shock, vol. 18(2), pp. 75-78, 1999.
[9] H.M. Hashemian, “Maintenance of process instrumentation in nuclear power plants,” Springer, 2006.
[10] G.Y. Zhao, Signal analysis and processing, Beijing: Mechanical Industry Press, 2006.
[11] Fei Si technology, MATLAB 7 counseling signal processing technology, Beijing: Electronic Industry Press, 2005.
[12] J.P. Chang and H.L. Li, Random signal analysis, Beijing: Science Press, 2006.