The Design and Implementation of a Vibration Fault Detection Cyber-Physical System

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Abstract. In this paper, the design and implementation of a vibration fault detection cyber-physical system (VFDCPS) is presented. Vibration fault detection is increasingly used in track vibration, bridge vibration and related fields. However, current research reveals some problems such as low accuracy of fault detection, few effective in-depth calculation of vibration data and fault test methods. Cyber-Physical systems (CPSs) are integrations of computation, networking, and physical processes. From the CPSs point of view, VFDCPS consists of three layers: the monitoring and control layer (MCL), the network layer and the device layer. The MCL deals with real-time monitoring and the precise control of the system. In the network layer, the CANopen network of field device can communicate with the Ethernet of VFDCPS for system's expandability and reliability. The device layer copes with collected data by using fast Fourier transform (FFT), lowpass filter, etc., which greatly improves the system's accuracy and the ability of massive computing. This paper also proposes a fault detection algorithm with vibration data called Spider which quantifies the criteria of fault evaluation. It is shown by test data that our approaches and improvements in design make VFDCPS more accurate and reliable in real-time vibration fault detection.

Introduction

In recent years, the application scenario of vibration fault detection has become wider, such as marine facilities vibration detecting, track vibration detecting and bridge vibration detecting. Reference [1] presents preliminary results towards an automated monitoring system for the quality assessment of insulated rail joints based on axle box acceleration (ABA) measurements, and reference [2] presents a prototype for monitoring and detecting the damage for the real bridge using those sensor nodes. However, the related fault detection techniques [3,4] have low accuracy, the vibration data are not analyzed in depth, and they haven't designed an effective system architecture.

CPS is a multi-dimensional complex system in which physical world operations are monitored and controlled using the communication and computing components, and they interact with each other in order to achieve a global optimization of such system operation [5]. With the development of CPSs technology, the achievement of VFDCPS is possible and we can take advantage of these merits in our VFDCPS. However, we have not found an effective fault detection system using CPSs approach till now.

Industry is an important application area of CPSs [6]. Controller Area Network (CAN) with real-time, reliable, economical and flexible features plays an important role in the industrial fieldbus area [7,8]. CANopen is a higher-layer protocol for the CAN [9]. Therefore, the VFDCPS device integrated CANopen protocol can make the system easier to control and expand. However, the field devices with CANopen function are mostly dedicated modules, thus it is inconvenient to secondary develop and integrate into the CPSs.
In this paper, we design a system architecture of VFDCPS. The experimental data showed that the performance of the system is improved significantly, especially in massive calculation and detection accuracy. The main work of this paper is as follows: 1) Designing a VFDCPS architecture, which is helpful to promote the development of technology in fault detection. 2) Proposing a fault detection algorithm called Spider, which takes both the characteristics of vibration data in the time domain and frequency domain into account and quantifies the fault evaluation criteria. 3) Achieving complicated computation in field device, such as FFT and low-pass filter, which greatly enhances the system's accuracy and ability of massive computing. In addition, we use RT-Thread real-time operating system (RTOS) for embedded devices to schedule tasks, which can improve the real-time performance and robustness. Furthermore, it is at the device board that we use software to achieve the function of CANopen protocol to integrate into the CPSs and lower the cost, and we use the latest high-precision accelerometer (provides an internal 20-bit analog-to-digital converter) to improve the detection accuracy.

The remainder of this paper is organized as follows. In Section 2, we present the related work. In Section 3, we describe the architecture design and implementation of VFDCPS, and the focus of this section is the design of field device. In Section 4, we present the process of vibration data in device layer and fault detection algorithm—Spider. In Section 5, firstly, we give the experiment environment and methods, and then analyze the experiment results. Finally, in Section 6, we give the conclusions.

Related Work
In this section, firstly, we introduce the current research status of fault detection with vibration data and the relevant knowledge. Secondly, we analyze the CPSs approach to vibration fault detection.

Fault Detection with Vibration Data
There are some researches and applications that use the vibration data to detect whether the devices or facilities are faulty or not [1,2,4,10]. However, most of them only do a simple treatment with the vibration data which causes low accuracy. Meanwhile, the study determined whether fault or not by artificial judgment because there exist few quantitative fault detection algorithms.

Reference [1] presents preliminary results towards an automated monitoring system for the quality assessment of insulated rail joints (IRJ). And IRJ with surface degradation is shown in Fig. 1.

![IRJ with surface degradation](image1)

![Acceleration and PSD at the IRJs with rail surface deformation](image2)

Fig. 1. IRJ with surface degradation. Fig. 2. Acceleration and PSD at the IRJs with rail surface deformation.

The study uses the ABA method to detect whether the IRJ suffers from a severe degradation or not according to two main characteristics: the acceleration curve and the power spectrum density (PSD). The test results are shown in Fig. 2. However, the artificial comparison with characteristics was used to determine whether the degradation is severe or not instead of automated data processing. Besides, the research did not design a fault detection system architecture.

Reference [2] presents a prototype for monitoring and detecting the damage for the real bridge using wireless sensor nodes. The study identifies the damage using a continuous indirect monitoring approach under numerous cases. But the analysis of the collected data is only on the server side, and the analysis algorithm is not present for detail. That is to say the study did not process the vibration data deeply in device nodes, and did not have a quantitative fault detection method, either.
From the analysis of numerous cases and our long-term research, we can summarize that the current vibration fault detection technology has many problems: 1) Few in-depth calculation and analysis in vibration data. 2) Few effective algorithms to quantize the criteria of fault evaluation and mostly using the manual experience to determine instead. 3) Haven't designed an effective system architecture of vibration detection. 4) Low fault detection accuracy. These problems hinder the development of related industries and should be solved urgently.

**CPSs Approach to VFDCPS**

Cyber-physical systems are integrations of computation, networking, and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations [11]. Besides, CPSs detect or control a physical entity in a manner that is secure, reliable, efficient and real-time [12]. Reference [13] initiates the idea of applying CPSs in the transportation system sector. The solution is based on an on-board unit using wireless communication with a highway tollbooth to pass the tollbooth and avoid unacceptable delays. Reference [5,6,14] also uses CPSs approach to enhance their systems performance.

Therefore, if we can design a vibration fault detection CPS to meet the demand of massive computing, precise control, real-time communication, we will be able to achieve the goal of accurate fault detection and also can take full advantage of the CPSs' merits.

**Architecture Design and Implementation of VFDCPS**

**Architecture Design of VFDCPS**

The overview of VFDCPS's architecture is presented in Fig. 3. According to CPSs approach, it's mainly divided into monitoring control layer, network layer and device layer.

Monitoring control layer (MCL) consists of workstation, central control screen, server and other components which are interconnected by Ethernet. The workstation can monitor VFDCPS's data and remotely control the system. The central control screen can show the status of the entire system in real time. The server is used for mass computing and data storage. Network layer is responsible for uploading the data of the device layer to the MCL and transmitting the control commands of the MCL to the device layer. Furthermore, the transfer protocol between the network layer and the device layer is diverse, such as Ethernet, WiFi or USB protocol, which can be changed according to the application requirements. However, the connection protocol between network layer and MCL is generally uniform, mostly using Ethernet. Device layer includes lots of devices installed in the field to monitor field data. In this VFDCPS, it contains two kinds of device in device layer: CANopen master (CM) and CANopen slave (CS). Each CS is equipped an accelerometer in order to collect vibration data. CM manages all CS in its own CANopen network, and CM board can upload the data from its network to CPSs network layer. CM can be directly connected to the workstation using the USB serial protocol if they are close. Then the workstation is connected to CPSs network by Ethernet.
Each CS node can do a complex calculation of the vibration data independently, such as FFT, root mean square (RMS), low-pass filter, which improves the fault detection accuracy and the ability of massive computing of the system. There are two main aspects of work that need to be done to implement the VFDCPS: UCS and field device. Upper computer software (using USB serial protocol as an example) is designed to have the function of USB serial communication, data processing and analysis, remote control and real-time display. The design of field device includes two parts: hardware design and software design. And it is designed to have the function of vibration signal acquisition, vibration data processing, CANopen protocol communication, Spider algorithm, abnormal emergency alarm and so on.

In other words, the following functions need to be implemented in VFDCPS:

- Upper computer software (UCS, running in Operator Workstation) is possible to communicate with CM through Ethernet, WiFi or USB protocol, as well as monitors and controls the system real-timely.
- CM is possible to collect the vibration data of all CS through CANopen protocol, and upload data to network layer in real time through Ethernet or other means.
- Each CS can make a complex calculation of vibration data, and send the process data as well as calculation results to CM using CANopen protocol. It is possible to timely alarm and perform emergency actions in exceptional circumstances.

**Design and Implementation of Field Node in Device Layer**

There are CM and CS two kinds of devices in device layer, and these devices are able to detect vibration, process vibration data, upload data, accept control signal and act according to the order. Besides, CM also needs to manage its CANopen network and communicates with Ethernet or other protocols, in order to join the VFDCPS network.

**Hardware Circuit Design of the CAN open Node in Device Layer**

The principle of hardware circuit design of the CANopen node is the low cost, miniaturization and reliable performance. Both CM and CS boards use STM32F4 as micro-programmed control unit (MCU) in order to achieve complicated computation and network management.

The circuit design of CANopen master board is presented in Fig. 5. It mainly consists of STM32F4 minimum system circuit, power circuit, CAN2.0 circuit and USB Serial, Ethernet or WiFi circuit. In addition, USB Serial, Ethernet or WiFi circuit can be tailored according to the application scene, which can reduce the cost and volume.
The circuit design of CANopen slave board is presented in Fig. 6. It mainly consists of STM32F4 minimum system circuit, power circuit, CAN2.0 circuit and ADXL355 accelerometer circuit. The use of accelerometer to detect vibration is a common and effective method. In this study, we use the latest ADXL355 accelerometer chip, which was designed by ADI (Analog Devices, Inc.) and had come to market in Sept., 2016. ADXL355 has the character of high accuracy (256000 LSB/g, 20bits), low drift and low power, which is compatible for our application. The physical map of the designed device board is shown in Fig. 7.

**Software Framework Design of the CANopen Node in Device Layer**

The stable operation of the device layer is the basic requirement of VFDCPS. The software framework of CANopen node is presented in Fig. 4, which contains application layer, protocol layer, driver layer and physical layer. And we use RT-Thread RTOS for embedded devices to control the system. RT-Thread kernel is core of the system, which provides object container, real-time scheduler, multi-thread management, inter-thread communication, etc.

The software task is surely different between CM and CS. There exists Ethernet application, CANopen application and serial port application in application layer, and CS only needs CANopen application. Protocol layer contains CANopen protocol, LwIP (Ethernet protocol), etc., and CS only needs CANopen protocol. Driver layer contains CAN chip driver, ADXL355 driver, USB serial driver, etc., and we can cut the ADXL355 for CM because it doesn't need it.

**Task Management with Rt-Thread Real-time Operating System**

In RT-Thread RTOS for embedded devices, each task can be realized by one or more threads. Threads are the basic scheduling units in RT-Thread, and they describe the context in which a task is executed and the priority of this task [15]. Important tasks will have a relatively high priority, and on the contrary, unimportant tasks are lower.

In memory management, RT-Thread provides a different memory allocation management algorithms according to the upper application and system resources. In general, it can be divided into two categories: static partition memory management and dynamic memory management.

**Table 1. The design of the allocation of resources and the thread settings of the main task.**

<table>
<thead>
<tr>
<th>Thread Name</th>
<th>Priority*</th>
<th>Stack (Byte)</th>
<th>Size</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>threads init</td>
<td>10</td>
<td>1024</td>
<td></td>
<td>All threads initialization</td>
</tr>
<tr>
<td>adxl355</td>
<td>11</td>
<td>1024</td>
<td></td>
<td>Get vibration data</td>
</tr>
<tr>
<td>CANopen</td>
<td>12</td>
<td>1024</td>
<td></td>
<td>CANopen Protocol</td>
</tr>
<tr>
<td>datadeal</td>
<td>13</td>
<td>512</td>
<td></td>
<td>Data Processing</td>
</tr>
<tr>
<td>USB_serial</td>
<td>12</td>
<td>512</td>
<td></td>
<td>Serial transmit</td>
</tr>
<tr>
<td>EEP_24C08</td>
<td>12</td>
<td>128</td>
<td></td>
<td>Data backup</td>
</tr>
<tr>
<td>WatchDog</td>
<td>15</td>
<td>128</td>
<td></td>
<td>Watch dog keeping</td>
</tr>
</tbody>
</table>

*The smaller value, the greater priority.*
The design of the allocation of resources and the thread settings of the main task in this study are shown in the Table 1. Reading ADXL355 accelerometer data is an important task, so the priority of the task is relatively high. And each data set of that task is larger, so it need larger memory. On the contrary, we set the watchdog task with lower priority in order to prevent the program from running abnormally.

**Data Processing of Vibration Data in Device Layer**

The original vibration data comes from the ADXL355 accelerometer, which requires preprocessing like zero-adjusting and noise removal, and after that the data can be used for calculations in practice. According to vibration data, we can get peak value, RMS and other characteristic parameters in time domain. However, more accurate VFDCPS requires the center frequency, PSD and other parameters in frequency domain. So it is necessary to carry out digital filtering, fast Fourier transform (FFT) and other processing.

The data processing in field device is shown in Fig. 8. First of all, the device do the filtering and other preprocessing after getting original vibration data from ADXL355 accelerometer. Secondly, do RMS, FFT, PSD, etc. calculations. Then the fault detection algorithm called Spider is used to calculate. Finally, field device output the fault information. Both the original sensor data and the processed data are output to VFDCPS and storage in servers for further processing.

![Fig. 8. The data processing in field device.](image)

**The Preprocessing of Accelerometer Data**

In this study, the preprocessing of accelerometer data mainly includes zero-adjusting and noise removal. The purpose of zero-adjusting is to make the accelerometer with a value of zero in the quiescent state. And we use low-pass filter to remove noise because the original vibration data contains high-frequency noise.

1) Zero-adjusting: In the actual installation process for device board, it is difficult to install the accelerometer perfectly horizontally or vertically, that's the reason why we need zero-adjusting by software. The data curve of static ADXL355 is usually like the red curve in Fig. 9. As is shown in Eq. 1, the most common method is to subtract the adjusting parameter "e".

\[
\text{Acceleration}_X(i) = \text{acceleration}_X(i) - e
\]

The parameter "e" is usually equal to the mean value of acceleration data when the accelerometer is static. For example, The mean value of the red line at this time is 0.033, so we let \( e = 0.033 \). The data curve after adjusting is the black one in Fig. 9, so we achieve the desired effect that the static acceleration data curve is mostly near zero.

2) Noise removal: The original vibration data contains high-frequency noise, especially the accelerometer is running in a vibrating environment. The use of low-pass filter can reduce the noise effectively, therefore, the vibration curve can be more smooth and true. In this design, a 30-order finite impulse response (FIR) low-pass filter is used to remove high-frequency noise.
Calculation of Characteristic Parameters for Vibration Data

Only after calculating and obtaining the characteristic parameters (CP) of the vibration data can we analyze the data better. The CP in time domain includes mean, RMS, standard deviation, peak value, etc. [16]. Meanwhile, the CP in frequency domain includes maximum amplitude, PSD, etc. [17]. And obviously we need to use FFT with the data.

After long-term investigation, research and experiment, this paper mainly uses the following CP of vibration data:

- Amax -- the average peak value of acceleration
- RMS -- the root mean square of the data
- PSDmax -- the maximum of power spectrum density

Amax stand for the average peak value of acceleration curve. And the main calculation steps for other CP are given here. In the case of a set of n vibration values (Xn), the RMS

\[ x_{rms} = \left( \frac{1}{n} \sum_{i=1}^{n} x_i^2 \right)^{1/2} \]  

Fourier analysis converts a signal from its time domain to a representation in the frequency domain. Let \( x_0, x_1, ..., x_{N-1} \) be complex numbers, and the FFT is defined by the equation (3).

\[ X(e^{jw}) = \sum_{n=1}^{N-1} x_ne^{-jnw} \]  

PSD describes how the power of a signal or a time series is distributed with frequency, that is

\[ S(e^{jw}) = \left| X(e^{jw}) \right|^2 \]  

Where \( w \) is the angular frequency.

The Spider Algorithm of Fault Detection

According to the physical meaning of the above characteristic parameters, consulting relevant information as well as long-term testing, we design a fault detection algorithm called Spider with vibration data, which is running in device node. And from another point of view, the difference of the CP between the normal and abnormal conditions has certain laws and can be used in Spider.

The core idea of Spider is comparing the detected vibration signal with the normal signal, and to determine whether the vibration is faulty or not by the abnormal degree (AD) of them. The equation of Spider as follow:

\[ AD = a \frac{x_{peak,i} - x_{peak,0}}{x_{peak,0}} + b \frac{x_{rms,i} - x_{rms,0}}{x_{rms,0}} + c \frac{x_{psd,i} - x_{psd,0}}{x_{psd,0}} \]  

Where \( x_{peak,0}, x_{rms,0}, x_{psd,0} \) are constants, and they remark the value of Amax, RMS, PSDmax respectively in normal condition. a, b, c are constants, and the effect is to adjust the weight of each eigenvalue to improve the accuracy of the algorithm. In general, we can let \( a=1, b=1, c=1 \).

The meaning of other symbols in Eq. 5 are shown here: 1) \( x_{peak,i} \) -- The Amax of the data to be detected. 2) \( x_{rms,i} \) -- The RMS of the data to be detected. 3) \( x_{psd,i} \) -- The PSDmax of the data to be detected.

If \( AD > AD_{Critical} \), the algorithm will output "fault". AD_Critical stands for the critical value of AD, which is usually slightly larger than the AD value under normal conditions. As we can see in Eq. 5, Spider has normalized the characteristic parameters of the vibration data firstly. Besides, users can adjust the weight of each CP according to the actual situation. It is easy and flexible to use, and has high accuracy in our test.
System Test

To evaluate the correctness and rationality of VFDCPS, we have done sufficient testing for each part of the system. Such as whether the CANopen protocol is working properly, whether the Ethernet and USB serial protocol of the CPSs network layer are working properly, whether the vibration data collection and calculation are working properly, whether the fault detection algorithm (Spider) is accurate and reasonable. Due to space constraints, this paper only presents the core part of the test methods and results.

Framework of the Test System

The framework of test system is shown in Fig. 10. One vibration platform can equip many CANopen slave boards (CS), and they are interconnected to CANopen Master board (CM) by CANopen network. CM and personal computer (PC) in workstation are connected by USB. And PC is connected to CPSs network.

The structure of vibration test platform and the physical map of vibration test system are shown in Fig. 11. "1" is the electric power source, "2" is the vibration platform, "3" is the PC. "4" is the vibration motor which fixed to the platform, and "5" is CS which is fixed on the platform. CS and CM are connected by CANopen, and CM and PC are connected by USB.

CANopen Network Test

We use software to achieve the function of CANopen protocol. Then we connect the CS to the CANopen analyzer, and judge whether each data frame is correct by the analyzer.

The test results are shown in Fig. 12. Firstly, CS sent a message of "Boot up" after power-on, and we can see that the node ID of CS is 0xD. Secondly, CM can normally respond a command message of "Enter Pre-operational State" to CS. Then CS sent a "PDO Data" message, which is the accelerometer data of CS. It can be seen that CANopen protocol is running normally.

Device's Computational Function Test

In this section, we test the CS's computational function of FFT and band-pass filtering (BPF). It should be noted that the MATLAB is only as a data curve display tool or as comparison in this study, and all the computations have implemented in the CS rather than simulation.
The CS and MATLAB are input the same vibration wave, then both run FFT, and the test results are shown in Fig. 13. We can see that the FFT calculation results between CS and MATLAB are same -- the center frequency is 7.2Hz, and the amplitude is 0.25. So the CS's FFT is correct.

This study uses MATLAB to generate 50Hz and 200Hz sine mixed wave, such as

\[ x = \sin(2\pi\cdot 50 \cdot t) + \sin(2\pi\cdot 200 \cdot t) + \sin(2\pi\cdot 350 \cdot t) \]

CS and MATLAB are input the same mixed wave and both of them run BPF (the band-pass frequency is between 125 Hz and 300 Hz). The test results show that the calculation results between CS and MATLAB are same -- only the frequency of 200Hz waveform. Therefore, the CS's BPF is correct.

The Test of Spider Algorithm

In order to illustrate the accuracy and practicability of the Spider algorithm, the vibration platform and the data of train track detection in reference [1] were used for testing in this section.

Motor Running Abnormally

Off-central load and other abnormal loads will cause great damage to the motor, and the Spider using motor vibration data which can detect these abnormalities. Different load can be configured on the motor to achieve normal and abnormal running of the motor. The vibration data of motor in the test is shown in Fig. 14.

Based on a number of tests under normal running, let

\[ x_{\text{peak}} \cdot 0 = 0.2218 \quad x_{\text{rms}} \cdot 0 = 0.1525 \]
\[ x_{\text{psd}} \cdot 0 = 0.1074 \]

and let a=1, b=1, c=1. Then run Spider, the results are shown in Table 2, the AD in "Running normally" is 2.9525, smaller than 10, so the result is Normal. Similarly, 42.2364>10, so
the result is Abnormal. In more than one hundred random tests, all the AD values of the normal running of the motor are between 0 and 4.9, and all the AD values of anomaly are greater than 26.8. Therefore, we can draw a conclusion that the accuracy of using Spider algorithm is extremely high in this test.

Table 2. The test of spider algorithm using motor data.

<table>
<thead>
<tr>
<th>Random test</th>
<th>Peak</th>
<th>RMS</th>
<th>PSD</th>
<th>AD</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running normally</td>
<td>0.2361</td>
<td>0.1632</td>
<td>0.1694</td>
<td>2.9525</td>
<td>Normal</td>
</tr>
<tr>
<td>Running abnormally</td>
<td>0.6411</td>
<td>0.4551</td>
<td>0.8704</td>
<td>42.2364</td>
<td>Abnormal</td>
</tr>
</tbody>
</table>

*Make AD < 10 for the motor running normal, otherwise is abnormal.

Railway Track Degradation

![Fig. 15. The vibration data of railway track.](image1)

![Fig. 16. PSD of railway track.](image2)

We use the data in Figure 4 of reference [1] to test Spider algorithm. The train travels at a speed of 100 km/h, and the vibration data of railway track is shown in Fig. 15. Assuming that the data of light degradation in the reference [1] fluctuating up and down within 20% belong to light degradation data. And we use this rule to randomly obtain many vibration acceleration data sets of light degradation condition.

In the case of light or severe degradation, the result of the calculation in CS is shown in Fig. 16, and the curves are consistent with reference [1]. Based on a number of tests under light degradation, let \(x_{\text{peak}} = 90\), \(x_{\text{max}} = 28\), \(x_{\text{psd}} = 205\) and let \(a=1\), \(b=1\), \(c=1\). Then run Spider, the following results are shown in Table 3, the AD in "Light" is 0.5637, smaller than 2.8, so the result is Light. Similarly, 6.5151>2.8, so the result is Severe. In more than one hundred random tests, all the AD values of the light degradation are between 0 and 2.2, and all the AD values of severe degradation are greater than 5.6. Therefore, we can draw a conclusion that the accuracy of using Spider algorithm is extremely high in this test.

Table 3. The test of spider algorithm using railway data.

<table>
<thead>
<tr>
<th>Random test</th>
<th>Peak</th>
<th>RMS</th>
<th>PSD</th>
<th>AD</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>103.81</td>
<td>32.81</td>
<td>253.82</td>
<td>0.5637</td>
<td>Light</td>
</tr>
<tr>
<td>Severe</td>
<td>177.34</td>
<td>53.99</td>
<td>1151.4</td>
<td>6.5151</td>
<td>Severe</td>
</tr>
</tbody>
</table>

*Make AD <2.8 for light degradation, otherwise is severe degradation.

Conclusion

In this paper we design a vibration fault detection cyber-physical system (VFDCPS). The VFDCPS includes monitoring and control layer, network layer and device layer. The study has completed the following works: firstly, it is at each CS in device layer that VFDCPS achieves complex calculations such as FFT, low-pass filter to improve the system's accuracy and calculative ability.
Secondly, the study creatively proposes a fault detection algorithm with vibration data, which has quantified the fault evaluation criteria. Finally, we use software to achieve the function of CANopen protocol to better integrate into the CPSs and lower the cost. Through a wide range of test, we find that each function of the system is working properly, and our improvements and innovations make VFDPCS more reliable and real-time. The test results also indicate that the fault detection algorithm—Spider is extremely accurate and reasonable compared with other existing approaches. In conclusion, we have achieved the intended result, which is helpful to promote the development of vibration fault detection in track vibration, large-scale machine vibration and other related fields.

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