Base on Embedded Fault Early Warning Control System on the Baler Gearbox

Bai Dong, Ren Bin
School of Mechanical Engineering
Shijiazhuang Tiedao University
Shijiazhuang, China
1519846416@qq.com

Xie Hu*
Nanjing Research institute for Agricultural Mechanization
Ministry of Agriculture
Nanjing, China
tmjamexh@163.com

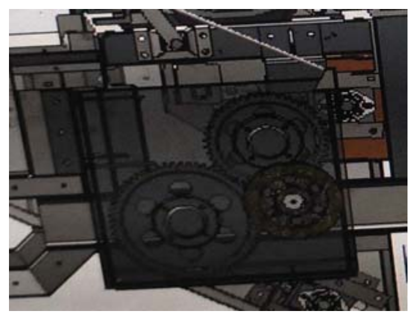
***Abstract*—Continuous operation baler can effectively improve baling efficiency, but the failure of gear box, the key functional part of working system of baler, will seriously affect its normal baling work and even cause more serious system breakdown. This paper introduces a fault detection and alarm control platform for gear transmission system, which is based on MCU (Microcontroller Unit) and DSP (Digital Signal Processor) as system hardware, spectrum analysis and BP neural network algorithm as system software. The signal can be obtained by the vibration sensor, and the faults will be judged by comparing the peak value of the spectrum with the threshold. After fault warning, the motor system of baler can be automatically adjusted and controlled, and the fault analysis can be realized by BP neural network, the fault positions and types are accurately predicted. The feasibility of the method has been verified by establishing the fault early warning experimental platform, which proves the method can effectively realize the identification the fault occurrence and early warning, and the self-healing regulation and failure analysis of the baler. The method provides the key technology foundation for preventing the breakdown and deterioration of the gearbox of baler.**

Keywords-Fault diagnosis; BP neural network; MCU& DSP;baler

I. INTRODUCTION

The improvement of the straw feeding system enables the continuous baling function of the continuous operation baler to be realized. But because of the requirement of continuous operation of the baler, the internal bearings, gears and other parts of the baler gearbox need continuous operation with high speed and high load, making the gear box more prone to fatigue spalling and high working temperature, which will lead to mechanical failure. The normal operation of the machine will be affected by the gear box failure first, which will make the baler have to be repaired and lead to the reduction of work efficiency, and other shafts, gears and bearings will be affected by the vibration generated by the failure of individual components, which increase the overall damage degree and the cost and difficulty of maintenance. The continuous operation baler is shown in Fig. 1 (a), and the 3D model diagrams of the baler gear box is shown in Fig. 1 (b).

(a) The continuous operation baler



(b) 3D model diagrams of the baler gear box

Figure 1. The continuous operation baler and gearbox

Vibration analysis is the most important method for current fault diagnosis and early warning, including time-frequency analysis, wavelet transform, HHT and so on, which have been widely used in the field of mechanical fault diagnosis. For example, Huang combines the neural network with the time-frequency analysis characteristics of wavelet transform [1]. The results of Bai Yahong were based on the empirical mode decomposition method and the support vector machine diagnosis method [2]. But high requirements has been put forward by the complex signal processing process and the neural network on the processor hardware, and it is difficult to give the feedback signal in time. In order to real-time warning of the failure signal of the baler gearbox can be realized and the occurrence of the fault signal can be judged accurately and control the work of the gearbox, a early warning control system which takes the DSP and MCU as the hardware system and

National Key Research and Development Program of China (No.2016YFD0701304)

978-1-7281-0860-5/19/$31.00 ©2019 IEEE

adopts the software algorithm of Spectrum analysis and BP neural network has been introduced in this paper, which realizes signal acquisition, fault warning, control and fault diagnosis of gearbox.

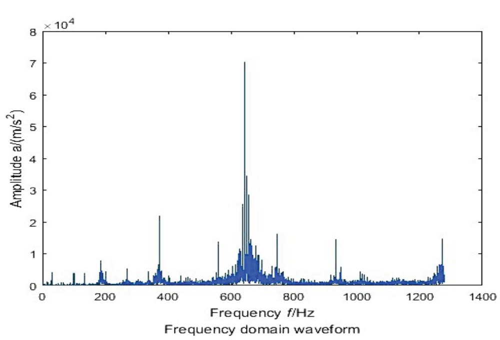
II. FAULT DETECTION METHOD

During the operation of the baler, the specific periodic pulse signal will be generated when the breakage of teeth, fatigue spalling and wear occur inside the gearbox. The pulse waveforms generated by different fault positions and fault types are different. In the fault diagnosis, these pulse waveforms can be collected and analyzed to ident the occurrence of the fault and the type of fault. Spectrum analysis, as a mature technology in engineering practice, the occurrence of faults can be judged accurately [3], and the FFT (Fast Fourier transform) butterfly algorithm can quickly process large amounts of data and save hardware memory. Compared with wavelet analysis or EMD technology, FFT is more suitable. Fault diagnosis by BP neural network was first introduced by Wasserman in the field of bearing fault diagnosis [4], and reached the level of human experts in this aspect. The BP neural network has a simple structure and has advantages that other neural networks do not have in combination with hardware.

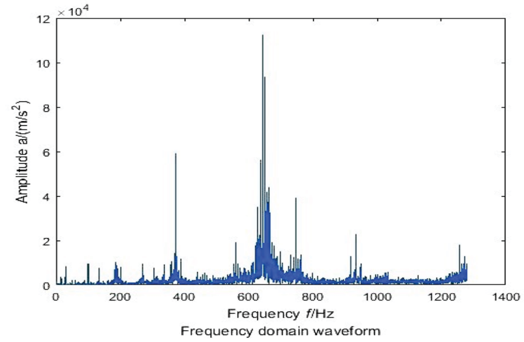
A. Spectrum Analysis

Frequency spectrum analysis is mainly based on fast Fourier transform to process the time-domain signals, and get the spectrum which the signal components at different frequencies [5]. Fault information can be reflected well by spectrum signal obtained from FFT, because the superposition of fault impulse signal and its high-order harmonic frequency components will increase the components of fault frequency in the spectrum. The fault occurs can be judged by setting a threshold value.

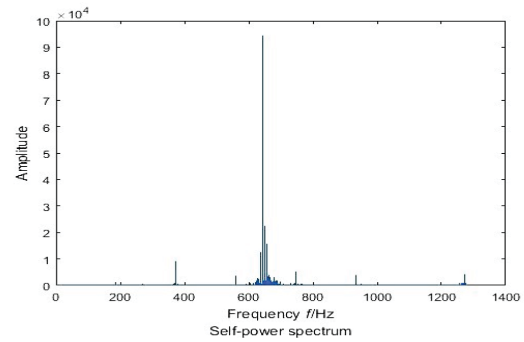
Fig. 2 is the experimental result of spectrum analysis, which is the vibration signal of a gear of the DDS power transmission fault diagnosis comprehensive experimental platform based on Matlab. Fig. 2(a) is the spectrum diagram obtained by spectrum analysis of the vibration signal of the normal gear. Fig. 2(b) is a spectrogram in which the gear is replaced with a broken gear. Comparing Fig. 2(a) and Fig. 2(b), what can be found that the spectral peak of the faulty gear is higher than the normal gear significantly. The experimental results show that the occurrence of the fault can be judged effectively by the peak values.



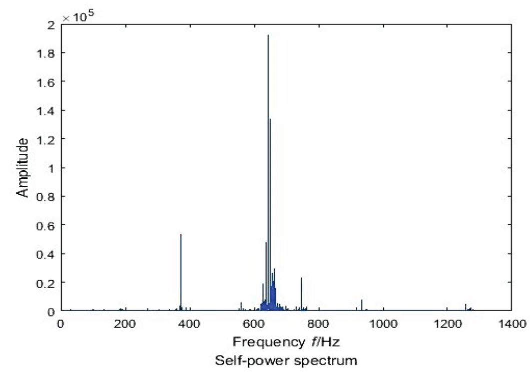
(a) Spectrum of the normal gear



(b) Spectrum of the broken gear



(c) Self-spectrum of the normal gear



(d) Self-spectrum of the broken gear

Figure 2. Spectrogram and self-spectrum

The self- spectrum is calculated on the basis of the spectrum which is a set of real data obtained by multiplying the complex spectrum by its conjugate and is better than the spectrum to judge whether the fault has occurred [6]. Fig. 2(c) and (d) are the self-spectrums obtained by the self-spectral calculation equations of Fig. 2(a) and (b) respectively. It is found from the spectrogram that the self-spectral relative spectrum can better reflect the occurrence of faults. Equations of the self-spectrum valuation:

$$S(x) = |x(k)|^2/N \tag{1}$$

Where:

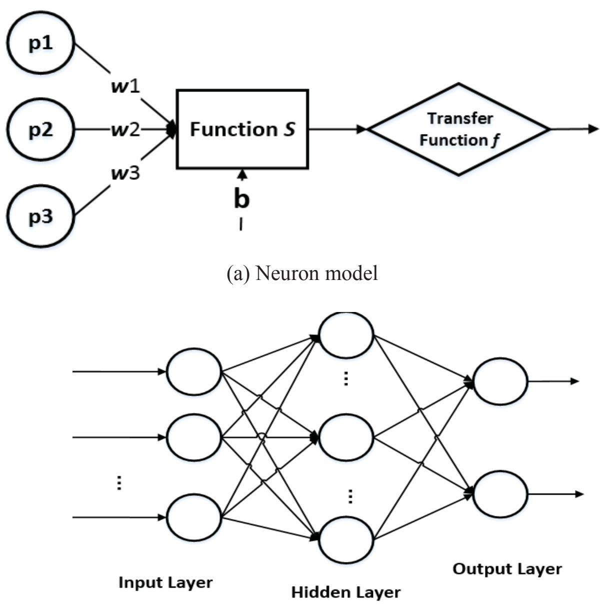
k=0,1,2…N-1

N——The number of sampling points

x(k)——The value of the time domain signal

B. BP Neural network

The method of analysis of fault signal mainly includes analytic method and neural network method. Among them, the precise mathematical model needed by the method of analytical is often difficult to establish [7], and the neural network does not need to analyze the internal processes or objects, but only needs to train the input and output data from the experiment to get the neural network model [8]. The neural network is composed of a plurality of neurons, and the neuron model is shown in Fig. 3(a), and Fig. 3(b) is a three-layer neural network model [9]. It can be seen from the figure that the neural network is divided into three layers: input layer, hidden layer and output layer. The front layer inputs are p1, p2, and p3, and their weights are ω1, ω2, and ω3, the characteristics of the neurons themselves are achieved by the internal intensity value b, the equation is $S = p1 \times \omega 1 + p2 \times \omega 2 + p3 \times \omega 3 + b \times 1$. The S value is converted to the output value f(s) by the mapping relationship of the transfer function and transmitted to the next layer of neurons. The transfer function of this paper uses the classical Sigmoid function.



(a) Neuron model

(b) Three-layer neural network model

Figure 3. Artificial neural networks

The weight value ωi and the internal strength value b of the neural network can be set by the in-software matrix, and the values of ωi and b need a lot of training to be corrected in practice. BP neural network is a multi-layer feedforward neural network trained according to the error back propagation algorithm. The input template is transmitted from the input layer and transmitted to the output layer through each hidden layer. If the actual result cannot be obtained by the output layer, the error will be reversed layer by layer in the reverse direction, and the error will be distributed to all units at each layer, and then the ωi and b values will be corrected. The results of the new data input can be predict by trained neural network effectively.

The self-spectrum obtained by FFT of the vibration signal of the gearbox vibration signal gearbox contains a large amount of fault information. If the frequency domain of the self-spectrum is evenly divided into n segments, and the peak value of each frequency band and its corresponding frequency are calculated as eigenvalues, when n takes a larger value, the vibration signal accident details can be reflected by these eigenvalues accurately. Then, the neural network is trained by the measured data to obtain a BP neural network structure that can reflect the intrinsic relationship between these eigenvalues and fault information, and the diagnostic analysis of the fault signal can be realized by the neural network.

III. HARDWARE DESIGN OF SYSTEM

DSP (Digital Signal Processor) is a processor consisting of Large-Scale Integrated Circuit Chip to accomplish some signal processing tasks. And MCU (Microcontroller Unit) is a microcomputer system that integrates CPU, RAM, ROM and other functions into a silicon chip by using VLSI (Very Large Scale Integration) technology to realize data processing and automatic control.

In order to ensure efficient data processing, to reduce power consumption, and to facilitate the expansion of other functions, the combination of TMS320F2407A DSP and 89C52 MCU have been used as the system hardware. The main function of DSP is to collect and process signals, calculate the rotation frequency of each shaft, judge whether the fault has occurred and controlling the motor of Baler by Event Manager. Then the DSP sends the information to the MCU through the serial port when the fault was occurred. The information of position and type of the fault will be obtained by the information what inputted by MCU to the BP neural network, and displays the fault information on the screen. The system hardware diagram is shown in Fig. 4.

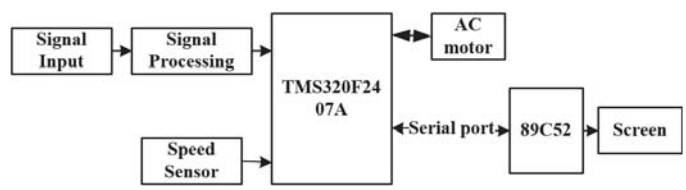


Figure 4. System hardware diagram

A. DSP module

The minimum system of TMS320F2407A consists of a clock circuit, a reset circuit, an extended memory and a power circuit [10]. The block diagram is shown in Fig. 5.

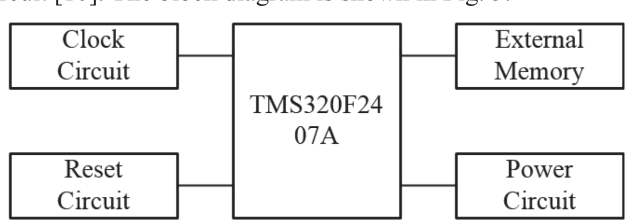


Figure 5. DSP minimum system

The DSP has built-in event manager EVA/EVB which provides strong control for motor [11]. The event manager includes general-purpose timers, comparators, PWM (Pulse Width Modulation) units, CAP (Capture unit), and QEP (Quadrature Encoder Pulse) circuits, as shown in Fig. 6.

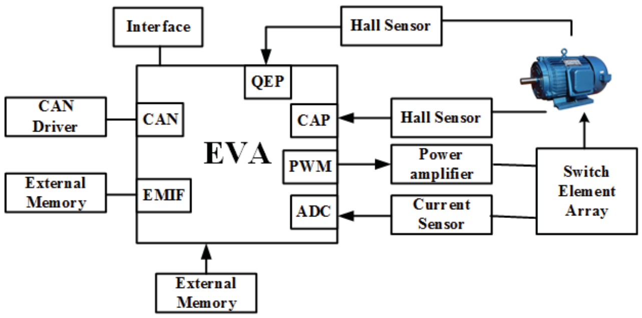


Figure 6. Event manager

B. Data Acquisition Module

The data acquisition module consists of a sensor, a charge amplifier, a low-pass filter and an A/D (Analog to Digital) converter. Since the signal collected by the sensor is weak and contains noise, the signal must to be conditioned before be transmitted to the A/D converter [12]. The acquisition module flow is shown in Fig. 7.

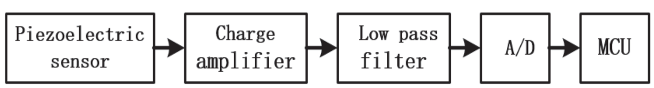


Figure 7. Signal acquisition process

The system uses a piezoelectric accelerometer as a vibration signal sensor that output power is linear with acceleration, and the piezoelectric accelerometer has the advantages of small volume, high sensitivity and wide frequency range. The charge amplifier proportional to the input and output is used as a secondary meter of the piezoelectric sensor for enhance the sensor signal.

Interference of noise can be reduced by the filter. The simple structure of the BUTTER WORTH switched capacitor low-pass filter MAX291 can be used to adjust the internal or external clock to select the cutoff range.

The TMS320F2407A DSP is internally equipped with a 10-bit A/D converter with an input voltage range of 0~3.3V, which basically meets the requirements.

C. Serial port module

The asynchronous serial communication has been used to the communication mode between the DSP and the MCU. Compared with SPI (Serial Peripheral Interface), DSP's SCI (Serial Communication Interface) is simple in structure and stronger in anti-interference ability. The 89C52 MCU is internally configured with a full-duplex serial communication interface. The baud rate can be set by setting the highest bit SMOD of the PCON register.

The output and input of SCI serial port are all 3.3V TTL level, and the transmission capacity is poor. The serial communication has been realized by RS-232C serial communication standard, and the chip adopts MAX232A duplex sending and receiving interface, as shown in Fig. 8.

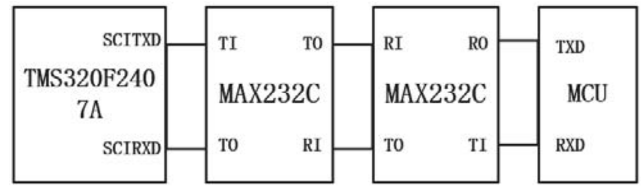


Figure 8. Serial communication between MCU and DSP

D. MCU module

In this paper, the 89C52 MCU is used as the hardware part of the neural network. The software is written in C language according to the specific algorithm of the neural network. The BP neural network is computationally complex and requires a large amount of code and tables. Therefore, the MCU uses 64K ROM and 12MHz Principal Frequency to improve the operating speed. The training of the neural network is completed on Matlab, and the parameters will be solidified into the program memory of 89C52 after training.

The main function of the screen in this system is to display the fault information and the signal of the speed information to the driver in an imaged form, which is convenient for the driver to operate. Considering the need for other feature extensions in the future, the human-computer interaction of this system uses a resistive touch screen OCMJ15×20D touch screen, which is not prone to be damaged and has a fast response speed, which is suitable for agricultural vehicles.

E. Shaft speed Measurement module

Hall speed sensor with smaller structure is used for rotating speed measurement. The sensor is mounted on the housing near the input shaft to detect the input shaft rotating speed, and the magnetic turntable is connected to the input shaft to be tested. When the small magnet of the magnetic turntable approaches the Hall unit when the shaft rotates, a pulse is generated on the Hall integrated switch sensor, the input shaft speed can be calculated by checking the pulse frequency [13], as shown in Fig. 9. By using the transmission ratio of gear box and the number of gear teeth, the rotational frequency of each shaft of gear box and the meshing frequency of each gear can be obtained. Compared with the photoelectric and magnetoelectric structures, the Hall-type rotational speed sensor has a simpler structure, higher frequency response, and stronger anti-electromagnetic interference capability.

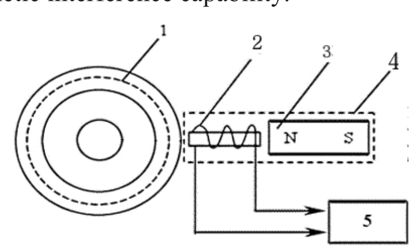


Figure 9. Hall type speed sensor

1.Magnetic turntable 2. Speed sensor 3. Permanent magnet 4. Induction coil 5. Adopt circuit

The pulse signal generated by the Hall unit is a sinusoidal wave electric signal. In order to obtain the standard pulse electrical signal, the circuit shown in Fig. 10 is used for conditioning.

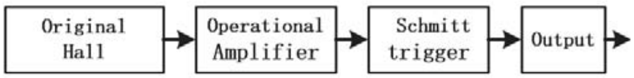


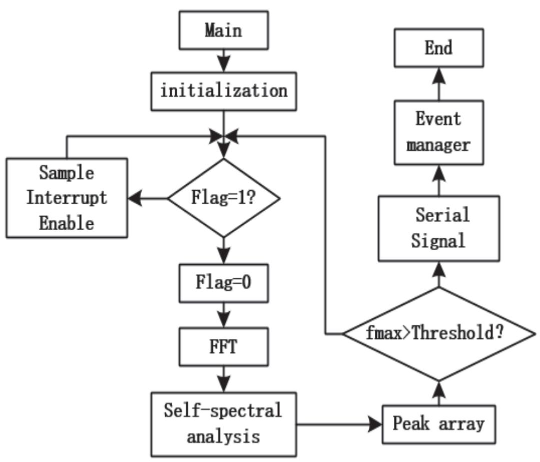
Figure 10. Speed sensor circuit

IV. SOFTWARE DESIGN OF SYSTEM

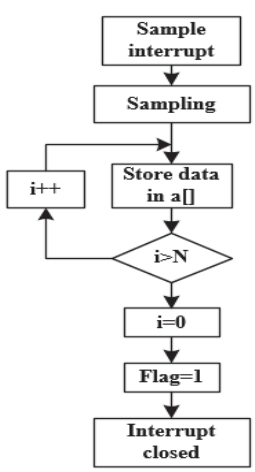
The system software is the core of the whole system. The DSP and MCU software are programmed with C language with strong logic and good portability, and recorded by CCS and Keil software respectively. In order to facilitate transplantation, the software is divided into main program, sampling module, neural network and signal processing module according to the principle of high cohesion and low coupling.

A. DSP software main Program module

The main program is the core of the entire software, composed of multiple functions that call subroutines, the Fig. 11 is the flow chart of the main program of DSP.



(a)



(b)

Figure 11. Main program

The initialization function is a sub-program which is first executed after the power-on of DSP, including the setting of sampling interrupt of rotating speed sensor and acceleration senor, initialization of event manager and serial timer, and the setting of sampling frequency and number of sampling points to ensure that the program can run correctly according to the prejudged mode.

The system continuously detects whether the sampling is completed, and the data obtained by the A/D converter has been stored in a one-dimensional array a[N]. After the sampling is completed, the interrupt is terminated, make Flag=1 and enter the data processing stage.

B. Signal Processing module

Discrete fast Fourier transform of signals has been realized by butterfly algorithm of FFT function. The complete program has been implemented in VS2013, which is not described in detail here. The characteristics of butterfly algorithm judge that the number of points N for FFT operation must be 2^m, if the number of sampling points is insufficient, it can make up for zero. When the signal in the time domain is converted to the signal in the frequency domain by FFT transform, the abscissa value of the Nth data point is the sampling frequency fs, the abscissa value of the first data point is fs/N, and the abscissa value of other data points in the middle are evenly distributed. Then, the frequency domain data obtained by FFT transformation are processed to obtain self-spectrum by equation (1).

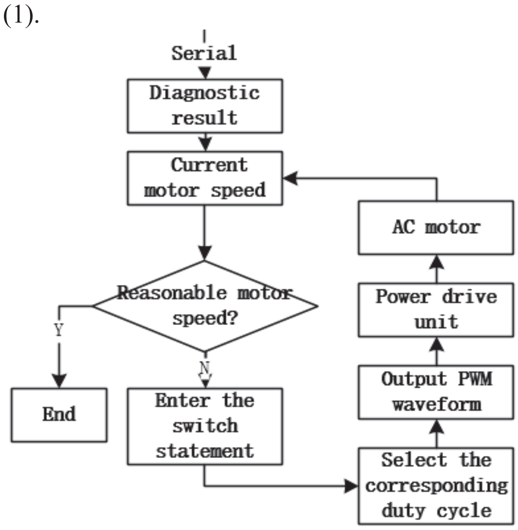


Figure 12. event manager

After the self-spectral analysis is completed, the frequency domain is divided into n/2 identical regions, where the larger the value of n, the more accurate the diagnosis result. This also demands a higher the hardware requirements. Then, the abscissa of peak values and peak values are searched in each region and stored in the array f[n] as fault eigenvalues. At the same time, the maximum fmax of peak values is extracted and compared with the pre-set threshold. If fmax is larger than the threshold value, it indicates that the baler gearbox is faulty, and the f[n] and the rotating speed of input shaft will be sent to the

MCU through the serial port. After the fault diagnosis is completed by MCU, the diagnosis result is returned to the DSP, and the PWM control signal is generated by the event manager EVA to complete the control of the motor, and the event manager control flow chart for the motor is shown in Fig. 12.

C. MCU software module

After the REN=1 is set by software, the receiver of MCU samples the RXD pin level at 4 times the selected baud rate. After the MCU receives the data sent by the DSP, the data in the f[n] and the rotation frequency of the input shaft are used as the data of input of the BP neural network. Because the rotational frequency of each shaft is linearly related to the rotational frequency of the input shaft, only the rotational frequency of the input shaft is input into the BP neural network. The MCU program is shown in Fig. 13.

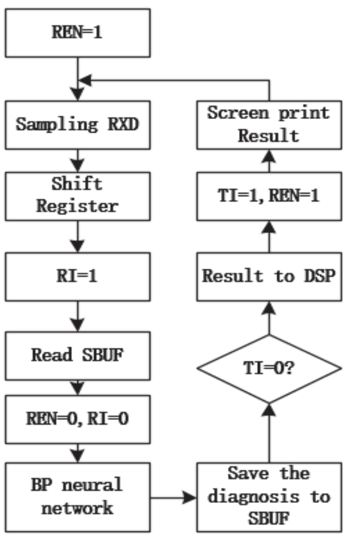


Figure 13. MCU program diagram

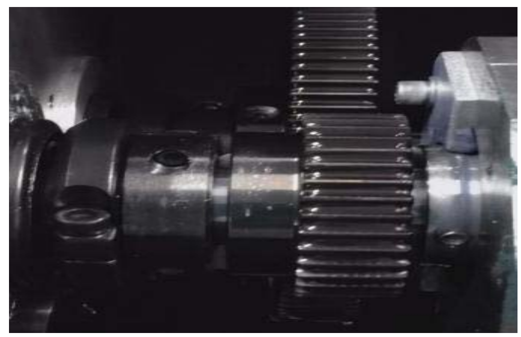
After the diagnosis results has been obtained by the calculation of each layer of the neural network, the diagnosis results will be printed the MCU to the screen in text format, and feeds back the results to the DSP through the serial port.

V. FEASIBILITY EXPERIMENTAL BASED ON DDS

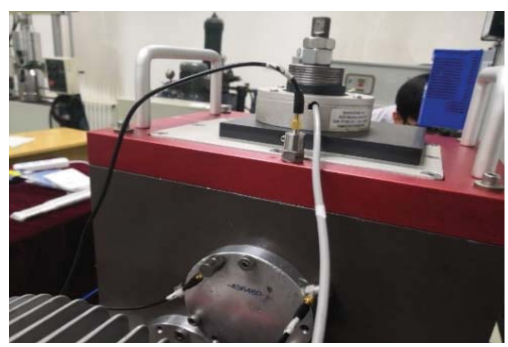
A. Feasibility analysis of Fault early Warning and Control

In order to verify the feasibility of the fault warning control system, the DDS power transmission fault diagnosis comprehensive experimental platform was used to simulate the baler gearbox. The DDS experiment platform is shown in Fig. 14(a). The bearings and gears in the gearbox of the DDS experiment platform can be replaced with inner ring wear bearing, outer ring wear bearing, broken gear and wear gear, as shown in Fig. 14(b). Download the signal acquisition and signal processing programs to the TMS320F2407A by the software CCS of the upper computer, and connect the acceleration sensor to the A/D port of the DSP. The control of the motor by EVA is simulated by the motor provided by the DSP, and the warning is realized by the buzzer provided by the DSP. In order to facilitate the observation of the experimental results, the computer is used to replace the MCU to realizes the fault diagnosis function of the neural network. The ICP piezoelectric acceleration sensor INV9822 from the COINV has been used to obtain signal, and the arrangement of the sensor is shown in Fig. 14(c).

(a) DDS Experimental platform



(b) piezoelectric accelerometers



(c) Replaceable bearing

Figure 14. DDS experimental platform

In order to set the threshold value A, the signal acquisition and analysis of the normal gear bearing, the wear gear, the broken gear, the inner ring and the outer ring wear bearing are respectively performed by the collector INV3062C and the software DASP under the condition of stable rotation speed. Then, each type of signal is collected in 30 groups, and each type of signal is taken in 5 groups for spectral analysis in DASP. The peak of each group spectrum is shown in Table 1.

By analyzing the self-spectrum of the vibration signal, the 1.2 times of the self-spectral peak of the vibration signal of the normal gearbox is taken as the threshold [14]. Then the threshold is written into the program, and the program is recorded to the DSP. After replace the gears and bearings of

TABLE I. TABLE 1 PEAK VALUES OF EACH GROUP

Normal gear and bearing	*Broken gear*	*Wear gear*	*Inner ring wear bearing*	*Outer ring wear bearing*
9.7751E4	1.7292E5	1.3518E5	1.2786E5	1.3717E5
8.6589E4	1.5677E5	1.4543E5	1.3395E5	1.3641E5
9.8644E4	1.6982E5	1.5833E5	1.4351E5	1.5152E5
9.1945E4	1.7377E5	1.4755E5	1.2813E5	1.3902E5
8.3222E4	1.6154E5	1.3638E5	1.3218E5	1.4200E5

the DDS experiment platform with the normal gear bearings, and turn on the power of the DSP, it can be found that the motor of the DSP rotates at a uniform speed and the buzzer does not alarm. After the bearing and gear have been replaced with faulty parts, an alarm signal has generated the buzzer, and the motor stops rotating immediately after starting work, as shown in Fig. 15. The experiment show that the system can effectively judge the occurrence of gearbox failure and provide early warning and timely control the motor.

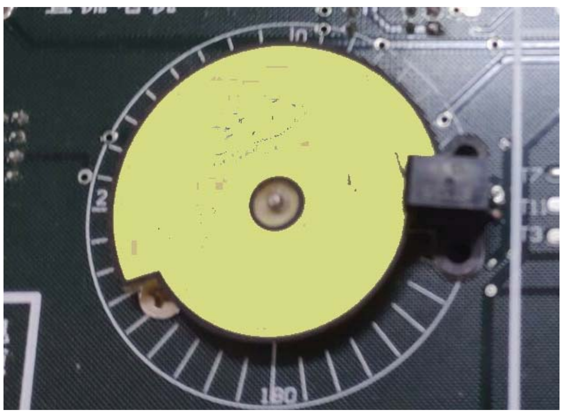


Figure 15. Motor

B. *Feasibility analysis of Fault diagnosis*

Organize the 30 groups of data collected in the previous experiment, the signals is self-spectrum analyzed by Matlab, and the frequency domain of self-spectral is divided into five segments. The peaks and abscissa of the peaks are obtained for each segment as the input characteristics of BP neural network. In the experiment, the input shaft speed was a constant value,, so the rotational frequency of shaft was not used as the input of the neural network.

After the fault signals has been collected and sorted out, 26 groups of fault signals were selected as training samples and the remaining 4 groups as prediction samples. The normal signal, broken teeth, wear, inner ring, and outer ring faults are replaced by the numbers 0, 1, 2, -1, and -2. Then construct a three-layer neural network in Matlab. The number of neurons in the hidden layer is 5, and the number of training is 500K. The specific settings are shown in Fig. 16.

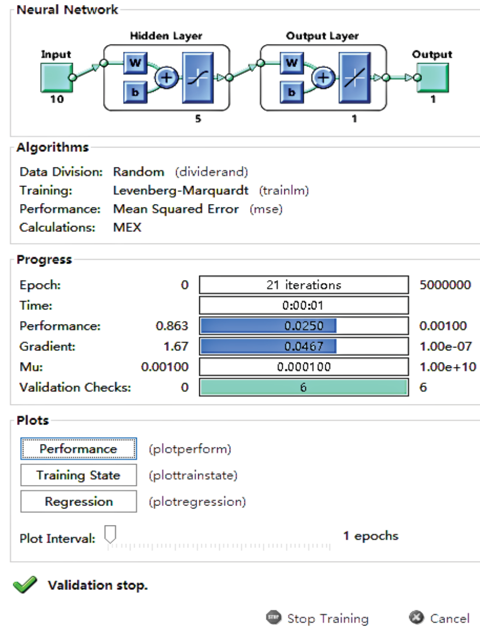
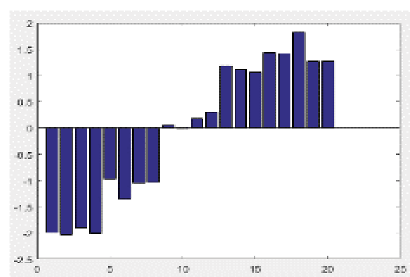
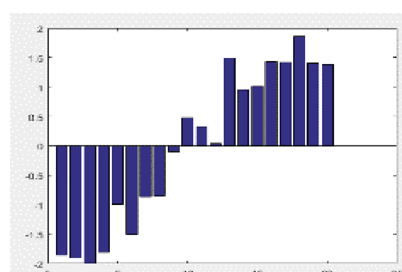


Figure 16. Neural network settings

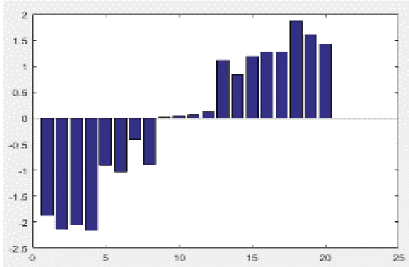
The predicted data are arranged in the order of outer ring, inner ring, normal, broken teeth and wear, with 4 groups of data for each type. The same data were tested three times in turn, and the prediction results are shown in Fig. 17 (a), (b) and (c). What can be seen from the figure that the first four sets of data are floating above -2, which means that the fault type is an outer ring fault, and the 5~8 groups floats above -1, which means that the fault type is an inner ring fault. Despite the failure to distinguish wear from broken tooth, which is due to the similarity of both types in terms of frequency, the neural network can accurately identify other fault types.



(a) First set of prediction results



(b) Second set of prediction results



(c) Third set of prediction results

Figure 17. BP neural network prediction results

VI. CONCLUSION

In view of the problem that the working efficiency of the baler is affected by the gearbox failure during the work process, the fault early warning control system has been introduced which is used DSP and MCU as hardware, combine the spectrum analysis and BP neural network as software to diagnose and control the gearbox fault. The signal acquisition has been realized by the acceleration and speed sensor, the analysis of spectrum and the judgment of fault occurrence are accomplished by DSP. The self-spectrum of fault signal is averagely divided into multiple frequency bands and peaks of each frequency band are extracted as eigenvalues, together with the input shaft rotation frequency as the input data of the BP neural network, and the fault information will be analyzed by BP neural network. The diagnosis result will be reported to the driver through an electronic screen, and a corresponding PWM signal can be given by EVA to control the motor according to the diagnosis result. In this paper, the feasibility of the method has been verified by establishing the DDS fault early warning experimental platform. The analysis results show that the occurrence of gear box faults can be judged effectively and early warning can be realized by buzzer, the motor can be controlled and the accurate diagnosis results will be obtained. The system is important for preventing sudden failures and fault deterioration, and the efficiency of the baler has been improved.

REFERENCES

[1] Huang Q, Jiang D, Hong L. Application ofwavelet neural networks on vibration fault diagnosis for wind turbine gearbox [M]. Advances in NeuralNetworks-ISNN 2008. Springer.2008: 313-320.

[2] BAI Ya-hong, WANG Feng-tao. Application of EMD Decomposition and Support Vector Machine Technology in Early Gear Wear Fault Diagnosis of Wind Power Gearbox[J]. Industrial Control Computer, 2010, 23(2): 70-71.

[3] Ding Kang, Li Weihua, Zhu Xiaoyong. Gear and gearbox fault diagnosis practical technology [M]. Mechanical Industry Press,2005.5

[4] WASSERMAN P D. On - line machine condition monitoring using artificial neural networks[J]. The Journal of the Acoustical Society of America, 1991, 90(4): 2324-2324.

[5] GAO H, LIANG L, CHEN X. Feature extraction and recognition for rolling element bearing fault utilizing short-time Fourier transform and non-negative matrix factorization[J]. Chinese Journal of Mechanical Engineering, 2015, 28(1): 96-105.K. Elissa, "Title of paper if known," unpublished.

[6] Frank P M. Fault diagnosis in dynamic systems using analytical and knowledge-based redundancy a survey and some new results, Automatic, 1990, 26(3):459～474

[7] Panos J A. Neural networks for control system[A]. IEEE Transactions on Neural Networks, June,1990,1(2):242~262

[8] Li Zhenan,Li Dengxiao. Single chip bearing fault diagnosis system [J]. Bearing,1992(03):48-52+61.

[9] Wu Ancheng. Neural network and deep learning [M]. Electronic Industry Press,2016.6

[10] Texas Instruments. TMS320LF/LC240xA DSP Controllers Reference Guide-System and Peripherals. SPRU357B.December,2001

[11] Su Kuifeng,Lv Qiang,Deng Zhidong.TMS320x28xxx Principle and development [M]. Electronic Industry Press,2009,3

[12] Wu Xiongying. Design of speech signal spectrum analyzer [D]. University of Electronic Science and Technology,2008.

[13] Zhu Zhenyu. Experimental Research on Automatic Control System of Automatic Variable Speed of Construction Vehicles [D]. Jilin University,2004

[14] Luo Xinjun. Using the single chip microcomputer to realize the fault diagnosis of the machine [J]. Coal mine machinery,1999(11):21-23.

[15] Qi Fang. Research on Equipment Fault Prediction Method Based on Extreme Learning Machine and Its Application [D]. Beijing University of Chemical Technology,2016.