Centrifugal Pump Bearing Fault Diagnose Based on Time-Frequency Domain Analysis and BP-Neural Network

Wang Chaowei\textsuperscript{1,*}, Zhou Guojing\textsuperscript{1}, Wu Qian\textsuperscript{2,b,*}, Ding Lvhui\textsuperscript{1} and Wei Yi\textsuperscript{1}

\textsuperscript{1}China Ship Develop and Design Center, Wuhan 430064, China
\textsuperscript{2}China National Institute of Standardization, Beijing 100191, China

E-mail: *wangcwbu@163.com; Corresponding Author: *bustbwuqian@163.com

Abstract. Fault refers to the loss of function of equipment during operation. When a fault occurs, the equipment would usually show some surface features, which can be also called fault signals. Thus, the faults of the equipment can be diagnosed by deep analysis. Among the mechanical and electrical products, the centrifugal pump is one of the most typical ones, which has the majority characteristics of equipment in various kinds of ordnance. Through the study of centrifugal pump fault diagnose, the route of diagnose of mechanical and electrical products and the establishment of diagnose system can be clarified. In the study, the composition and function of centrifugal pump is firstly introduced. So is the fault diagnose system. Then the concept of the fault diagnose experiment is given. The data gathered by the diagnose system are processed in time and frequency domain. The BP- neural network is also applied to analyse the pump’s fault which is injected during the experiment. The analysis result reveals that the BP- neural network can effectively estimate the condition of centrifugal pump and distinguish the different fault modes.

1. Introduction
Fault or failure refers to the event or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified. It usually causes the loss of functions of the equipment or system, which can lead to the failure of scheduled missions or the damage on person and environment [1]. The capability of rapid recovery much depend on whether the faults can be detected or isolated, or can be diagnosed in other word. So to improve the fault diagnose level is one of the key way to increase the operational availability of equipment [2].

In the paper, centrifugal pump, a typical mechanical and electrical product, is chosen as an example to study the feasible way of equipment fault diagnose. The composition and function of centrifugal pump and the fault diagnose system is introduced firstly. Then the concept of the fault diagnose experiment is given, which includes experiment time, section, fault component, fault inject method and the rules of data gathering. The bearing fault of centrifugal pump is the focus. The data of bearing fault is processed in time domain in advance. In addition, the feature parameter of bearing fault signals is also analyzed in frequency domain. Then the BP- neural network is applied to analyse the bearing’s different fault, including inner ring, outer ring and rolling elements. The analysis result reveals that the BP- neural network can effectively estimate the condition of centrifugal pump and distinguish the different fault modes. The consequence shows that the method of combination of time- frequency domain analysis and BP-neural network is efficacious and meet the engineering practical need.
2. Centrifugal pump and fault diagnose system

2.1. Centrifugal pump

2.1.1. Function. The centrifugal pump is used to transfer the given liquid with the centrifugal force which caused by the movement of impeller. The liquid in the channel would be driven into the pump shell by the centrifugal force, which lead to the decrease of the stress around the centre of impeller. The gap of stress made the liquid get into the shell again.

2.1.2. Composition. The common centrifugal pump usually consists of six parts: impeller, shell, bearing, main axis, seal ring and electrical motor. The alternating current drives the electrical motor runs. The electrical motor is linked to the main axis. Finally, the impeller is moved and controlled by electrical motor, as shown in Figure 1.

![Figure 1. Centrifugal pump composition](image-url)

2.1.3. Performance parameter. The performance parameters of centrifugal pump in the experiment are as followings: 1) Specified flow rate: 18m$^3$/h, 2) Specified lift: 24.5m, 3) NPSH (net positive suction head): < 3m H$_2$O, 4) Specified rotate speed: 2950r/min, 5) Specified power rate: 3kW, 6) Weight: 94kg

2.1.4. Requirements for functions and performance checking before experiment. Failure signal. The centrifugal pump have to be checked after being fixed onto the rack, which includes two parts: performance parameter, especially flow rate, and operation condition. The flow rate must reach the degree of 18m$^3$/h without leakage of oil and water. In the meantime, there is no abnormal noise in specified rotate speed.

2.2. Fault diagnose system

2.2.1. Composition. The fault diagnose system consists of three parts. The first one is data perception module that contains electric current sensor, flow rate sensor, vibration sensor and displacement sensor. The second one is data gather and primary-processing module, which contain the four outcomes and inputs of four kinds of sensors. It can be divided into two parts: data recuperating module and data gathering module. The inputs are linked by plugs. The third one is main fault diagnosis system, which contains original data module, time domain and frequency domain analysis module, feature value extract module and fault diagnosis module. The configuration of the fault diagnose system is shown in Figure 2.

![Figure 2. Configuration of the fault diagnose system](image-url)

2.2.2. Operation requirements of fault diagnose system. The part number and operation requirements of different module in the system is given in Table 1. The sensors is chosen according to the monitoring requirements. And the data gather and primary-processing module and main fault diagnosis system is developed according to the fault diagnose experiment requirements. The electric current sensor, vibration sensor and displacement sensor is fixed in the pump, and the flow rate sensor is fix on the pipe.
3. Fault diagnosis experiment concept

3.1. Establish of experiment system. The centrifugal pump must operation in a certain experiment system in order to accomplish the imitate of normal and abnormal condition. The centrifugal pump and the electrical motor is fixed to the iron framework with bolts. The side face of framework is also linked with substrate with bolts. The substrate's function is to support pump. Then the fault diagnose system should be connected with pump. Then four kinds of sensors should be fixed to the corresponding place so as to monitoring the fault signals effectively.

3.2. Experiment section. The centrifugal pump fault diagnosis experiment contains five kinds of different sections. The first one is centrifugal pump under normal operation, which amounts to 100h. All the four kinds data should be recorded every 2.5h. Hence 40 group data would be gathered. The second one is electrical motor fault injection, which amounts to 7.5h. The electric current signal should be recorded every 2.5h. Hence 3 group data would be gathered. The third one is main axis fault injection, which amounts to 30h. The displacement signal should be recorded every 2.5h. Hence 12 group data would be gathered. The fourth one is impeller fault injection, which amounts to 10h. The flow signal should be recorded every 2.5h. Hence 4 group data would be gathered. The last one is bearing fault injection. It can be divided into three part, inner ring fault injection, outer ring injection and rolling element injection. Each is 17.5h, which amounts to 52.5h. The vibration signal should be recorded every 2.5h. Hence 21 group data would be gathered, in which there are three kinds according to the experiment of bearding. In sum, the total time of experiment is 200h.

| No. | Name                  | Part No.            | Operation requirement                      |
|-----|----------------------|---------------------|-------------------------------------------|
| 1   | vibration sensor     | YD                  | frequency: 10–1kHz.                      |
| 2   | electric current sensor | YY-I              | range of measurement:±30A             |
| 3   | flow rate sensor     | LWGY                | 1) diameter of pipe: 50mm;                |
|     |                      |                     | 2) transmitter: water;                    |
|     |                      |                     | 3) flow rate: 18 m³/h                    |
| 4   | displacement sensor  | PMP                 | range of measurement:±10mV              |
| 5   | data recuperating module | AD620/TLC2262(YY-16) | maximum gain:2000                      |
| 6   | data gathering module | STM32F103ZE(YY-STM32)| 1) sampling rate: 10kHz                 |
|     |                      |                     | 2) number of data channel: 10            |
3.3. Requirement for experiment data gathering, recording and processing. 1) method of data storing: with the software (labVIEW) in main fault diagnosis system, 2) type of data storing: xlsx format, 3) sampling interval time:2.5h, 4) sampling frequency:20000Hz, 5) the data would be recorded with the fuction of report generation. It will help generate the report in word or excel format automatically, including date, environment, operator and fault diagnoses result.

4. Pump bearing fault diagnosis based on time-frequency domain analysis and BP-neural network

In the study, the impeller, main axis, and electrical motor's fault can be detected according to the monitoring signals directly. The problem of above three elements' fault diagnose is relatively simple. Therefore, the paper focuses on the diagnosis of bearing. The signal of vibration is applied to the diagnosis. The vibration would be preprocessed and time-frequency domain analyzed. The BP-neural network conduct the diagnosis finally.

4.1. Noise reduction and time domain of original analysis data. The three-dimensional vibration signal is gathering by the vibration sensor in the experiment. The original data's noise of three kinds of bearing fault has been reduced by the method of wavelet denoising. It shows that the noise level has been reduced. The same process progress is applied to another two group of vibration data. Then the relatively pure data can be used to extract and calculated the fault feature valve. The Fault feature valve of three-dimensional vibration is shown in table 2. This step is the foundation of fault diagnosis. Whereas it is difficult to determine the fault only from the time domain [4].

| Fault       | X     | Y     | Z     |
|-------------|-------|-------|-------|
| Inner ring  | -0.6600 | -0.3381 | -0.0907 |
| Outer ring  | 0.7007  | 1.1241 | 0.47057 |
| Rolling element | 0.4554 | 2.2888 | 1.0012 |

4.2. Frequency domain analysis. The frequency domain analysis of vibration signal is to calculate the bearing's main frequency. The analysis result of three kinds of monitoring data is shown in Figure 3, which is processed by Fourier transform (FFT). It can be noted that the main frequency of inner ring is 236.6Hz in the experiment, which basically coincide with the theoretical value 237.3Hz [5]. Through there is some distraction around 90Hz and 270 Hz, they wouldn't influence the main frequency. The same process progress has been conduct also in other two group of data, which are outer ring fault data and rolling element fault data.

Figure 3. Frequency domain analysis of inner ring fault vibration signal
4.3 BP-neural network analysis.

4.3.1. Training of sample data. It must be figured out that the assemblage should be full of the sample space when choosing the sample data for training. Aiming at the bearing fault diagnose, six elements of vibration signal are chose as feature valves to train the BP-neural network based on the different kinds of fault and data gathered. These feature valves are marked as V1-V6 for short. The first feature valve is range maximum [6]. The second one is range minimum. The third one is range mean value. The fourth one is core frequency. The fifth one is the number of feature frequency. The sixth one is mean value of variation. The expected outcome of the BP-neural network is expressed by the binary system “0”&”1”. The four condition of bearing is expressed as (1,0,0,0), (0,1,0,0), (0,0,1,0) and (0,0,0,1). The corresponding condition is normal, inner ring fault, outer ring fault and rolling elements fault. The target outcome of BP-neural network analysis is marked with T1-T4. The matlab (LM training function) is used to create the BP-neural network to meet the requirements above. The number of training time is set as 1000.

4.3.2. Test of BP-neural network analysis. After the training of BP-neural network analysis, the fault vibration signal data should be normalized before diagnosing. According to the experiment concept, seven group data has been recorder under the state of inner ring fault. All the seven group data are processed by the well-trained BP-neural network. As shown in table 3, the diagnose error can be summarized in the outcome of BP-neural network. The fault detecting error is nearly 4%, as shown in Figure 4. In other word, the accuracy rate of inner ring fault detect is 96%.

Table 3 Analysis data of inner ring fault

| No. | V1   | V 2   | V 3   | V 4   | V 5   | V 6   | Outcome of BP-neural network                  |
|-----|------|-------|-------|-------|-------|-------|-----------------------------------------------|
| 1   | 7.10 | -0.03 | 0.77  | 241.96| 25    | 8.56  | (0.0092,0.9584,0.0051,0.0062)                  |
| 2   | 7.48 | -0.04 | 0.74  | 241.96| 15    | 8.76  | (0.0087,0.9632,0.0068,0.0113)                  |
| 3   | 7.22 | -0.12 | 0.79  | 241.94| 26    | 8.67  | (0.0096,0.9620,0.0057,0.0074)                  |
| 4   | 7.64 | -0.45 | 0.77  | 241.99| 16    | 9.04  | (0.0088,0.9752,0.0062,0.0056)                  |
| 5   | 7.46 | -0.92 | 0.75  | 241.94| 24    | 8.64  | (0.0079,0.9654,0.0071,0.0106)                  |
| 6   | 6.78 | -0.02 | 0.71  | 242.13| 25    | 8.40  | (0.0069,0.9589,0.0072,0.0089)                  |
| 7   | 6.80 | -0.02 | 0.78  | 241.86| 21    | 8.41  | (0.0073,0.9687,0.0069,0.0073)                  |

Figure 4. Error curve of inner ring fault diagnose
5. Conclusion
This study presented a method of mechanical and electrical products analysis based on time-frequency domain analysis and BP-neural network. Based on the analysis of centrifugal pump composition, function and performance parameters, the corresponding fault diagnosis system is built. So is the experiment system. The concept of experiment is also given in the paper. The validity and valid of the method of time-frequency domain analysis and BP-neural network is verified through experiment. It reveals that BP-neural network has a certain practical significance for the water pump fault diagnosis research. The study way can guide the design of fault diagnosis system and other condition monitoring system.

References
[1] Chaowei Wang, Peng Li, Boren Chen, Xingpan Zhou, Design of Pump Fault Diagnosis System Based on T-FMEA[C]. 2018 2nd International Conference on Data Mining, Communications and Information Technology, 2018
[2] Ante Bukša, IvicaŠegulja. Ship system reliability[J]. Scientific Journal of Maritime Research 2008, 8.
[3] JIN Qiao, FANG Shuai, YAN Shi, LI Hong Nan. Methods to Improve BP Network[J]. Journal of Shenyang Ar ch. and Civ. Eng. Univ. China. 2001, 7: 197-200.
[4] WU Y Y, XING W S, ZHU X M, et al. Study on vibration characteristic of centrifugal pump [J]. Chinese Journal of Ship Research, 2008, 3(1): 51-54
[5] Zhou Zheng. Survey of Current Progress in BP Neural Network [J]. Shanxi Electronic Technology. China. 2008, 2: 90-92.
[6] LI Jun qing, CHEN He nian, YAN Lili, JI Wentian Evaluation Index for the Management Level of Computer Lab Based on BP Neural Network [J]. RESEARCH AND EXPLORATION IN LABORATORY. 2011, 4: 71-73.