Research and Design of Water Pump Diagnosis System Based on Wavelet Transform and DSP

Yongxian Song [1,2]
1. School of Electronic Engineering, Huaihai Institute of Technology, Lianyungang, China
Email: soyox@126.com

Kangde Zhao[2] and Yuan Feng [1]
2. School of Electronic and Information Engineering, Jiangsu University, Zhenjiang, China

***Abstract*—the running status of it can be more comprehensive judged through acquisition and analysis of vibration signal for water pump rotary machinery. Therefore, the collection of vibration signal is the key to monitor equipment running status and diagnose faults. This paper introduces water pump fault diagnosis system based on DSP and wavelet transform, and the system can realize water pump vibration signal acquisition and real-time fault diagnosis. In order to improve the vibration signal to noise ratio and get relatively pure vibration signal, the vibration signal that is collected is de-noised by the wavelet de-noising technology. Due to vibration signal often contain singularity component when the pump device occur fault, therefore, the fault diagnosis information of water pump can be derived from vibration signal singularity analysis, the vibration signal is processed and analyzed by combining the modulus maximum value of wavelet transform (WTMM) with *Lipschitz* index, and the fault characteristic values are obtained. The knowledge base of fault model is obtained by training a large number of fault characteristic values, and suspected fault sets are obtained according to model matching method, finally diagnostic results are received by the intersection of suspected fault sets. The experiment results show that the system can effectively find the faults, distinguish faults type and identify faults degree, a kind of effective method is provided for water pump unit faults diagnosis, and has the certain instruction significance for other mechanical fault diagnosis.**

***Index Terms*—DSP, Wavelet analysis, fault diagnosis, *Lipschitz* index**

I. INTRODUCTION

With the development of our country economy, the water resources play a more prominent role in industrial production and people's life, the pump unit is the core part of the water supply system, once the water supply system is failure, and the normal production and life of city will be affected. Therefore, the normal operation of water pump should be ensured, the state of it should be monitored and faults warming should be timely found, and the development direction of pump unit is advance the overhaul and nip in the bud, it is an important practical significance that ensure sustained and stable work of pumping station. With the development of modern science and technology, the water pump and other mechanical equipments are more and more complex, the fault reasons of water pump and other mechanical equipments are more and more too. The development of signal processing technology provides a new research method for faults diagnosis.

For the rotary device, the vibration signal has more direct reflection for the equipments state. At present, the rotary machinery faults discrimination based on vibration signal is the most commonly method at home and abroad. The method based on the vibration signal is most convenient and practical from the test means. If the faults are identified according to the vibration signal, first, the useful features information are extracted from the vibration signal, namely, the vibration signal was processed by the signal processing technique.

Wavelet analysis is time and frequency analysis method, its resolution is variable, it has good characterization capabilities in the time domain and frequency domain, and has adaptability for signal. It has a high time resolution and low frequency resolution at high frequency band of phase plane of the time and frequency, and it has low time resolution and high frequency resolution in the low frequency range. So the short-term frequency components in signal can be analyzed, the low frequency decreasing trend was estimated, and an effective method was provided for non stationary signal analysis, noise separation and feature information extraction in water pump faults diagnosis. Therefore, this article proposed pump faults diagnosis system based on wavelet transform and DSP.

The paper mainly includes the following aspects. First, the vibration signal acquisition system based on acceleration sensor MMA7260 and microprocessor uPD78F0547 is designed. Second, the wavelet transform is applied to water pump vibration signal de-noised, and it can better distinguish noise and vibration signal singularity, ruled out that the noise have an influence on signal singularity. Third, the signal singularity analysis technique based on the Lipschitz index is applied in water pump vibration signal features extraction, and the faults

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vibration signal can be more accurately depicted. Fourth, the knowledge base of faults model is established. A lot of data that contain normal and all kinds of faults information are obtained by the actual operation test of water pump. Last, the faults diagnosis of water pump is achieved by using model matching method. The vibration signal faults characteristic values of water pump are extracted in real time, and match with the corresponding sets data in the model knowledge base to get suspected fault sets according to fault model matching algorithm, thus obtain the suspected fault sets intersection and get the results of faults diagnosis.

II. The Overall Design Of System

The basic parameters of vibration detection have amplitude, frequency and phase. Amplitude is an important indicator of vibration level, and it can be represented by displacement, velocity or acceleration. Therefore, the vibration signal can be detected, that is, any one of displacement, velocity and acceleration is detected, and the other two physical quantities can be obtained according to differential or integration relation between them.

At present, the popular approach of vibration acquisition adopt acceleration sensor, and the system adopt an integrated acceleration sensor MMA7260 to detect pump unit vibration signal. In order to realize the rapid acquisition of vibration signal and take into account acquisition cost, TMS320F2812DSP chip is taken as the microprocessor, the chip internal has high speed A / D converter and a large capacity memory. The overall structure of system is shown in Figure.1. It is composed of main microprocessor module, vibration sensor module, communication module and PC. Due to it will produce vibration when water pump runs, the pump vibration signal is converted to electric signal by vibration sensor, vibration analog signal acquisition is realized through the internal high-speed A / D of DSP, and vibration data that is collected temporarily stored in the internal RAM, then the vibration data are converted to a host machine through the RS232 interface circuit. Due to vibration signal that is connected contain noise factors, in order to obtain pure vibration signal, vibration signal is de-noised by wavelet de-noise technology.

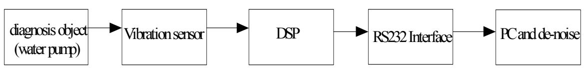

Figure.1. the overall structure of the system

III. Vibration Signal De-Noise Processing Analysis

A. De-noise Method Selection

In water pump state monitoring and faults diagnosis, in order to extract the signal characteristics, the measured signal is usually analyzed and processed. However, the vibration signal is often subject to the influence of various noise and interference. The fault information in signal is often flooded by strong noise, and it is great difficulty to extract the feature of faults signal. Therefore, it is very necessary to extract useful signal from noise signal and realize signal and noise separation. Signal de-noised is one of the important applications of wavelet analysis [1-3], in the practical application of wavelet de-noising, the signal that is analyzed may contain many parts of the peak or mutation, and the noise is not stationary white noise, for analysis of this signal, first, the signal need be pretreated, signal noise is removed and the useful signal is extracted. The traditional FFT analysis is incapable to realize the function above. Because the signal analysis is completed in frequency domain for FFT, it can't give the change of signal at a certain time point, any one mutation of the signal on the time axis will affect the entire spectrum signal, and wavelet analysis can simultaneously analyze signal in time frequency domain, and when the resolution is high in frequency domain, the resolution is low in time domain; when the resolution is low in frequency domain, the resolution is high in time domain. So the mutant part and noise in signal can be effectively distinguished, thus the signal de-noised is realized.

In *Matlab* , the wavelet signal de-noised is mainly achieved by the two functions $wden$ and $wdencmp$, in order to obtain the standard deviation of model, the input parameters of the function $wden$ need be set, i.e. $sd = wden(s, tptr, sorh, scal, n, 'wname')$. Function return value is sd that is the result of the de-noised original signal S . And $tptr$ indicates threshold selection rules, $sorh$ appoints the soft threshold and hard threshold, n is level of wavelet decomposition, $wname$ is designated wavelet in decomposition. Parameter $scal$ is the proportion that the scale of threshold value is changed.

One-dimensional signal can be directly de-noised by the $wdencmp$, namely, which achieved by quantizing wavelet decomposition coefficient thresholds, $xd = wdencmp(opt, x, 'wname', n, thr, sorh, keepapp)$. $opt = 'gbl'$, thr is a positive real number, and it is shown that threshold is a global threshold. $opt = 'lvd'$, it is a vector, and its threshold is numerical that size is different in each layer. When $Keepapp = 1$, the low frequency coefficients of wavelet decomposition will not do any processing. When $Keepapp = 0$, the low frequency coefficients of wavelet decomposition need be quantized. x is unprocessed input signal and xd is processed signal, and the rest parameters are the same as function $wden$. In order to verify the effect that wavelet de-noised, we compared the wavelet transform with FFT method by example, we add white noise to signal, it is shown in Figure 2, the signal with white noise is de-noised by the Fourier analysis method and wavelet analysis method respectively.

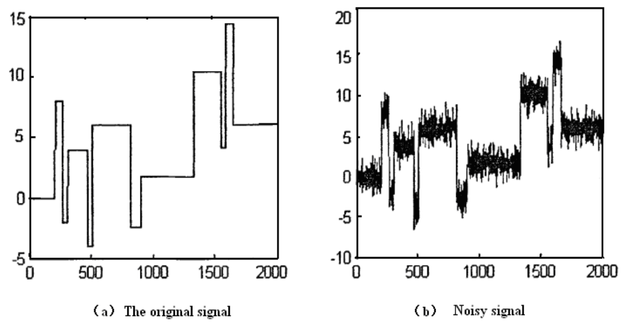

Figure.2. the original signal and noise signal

The signal with noise is de-noised by function $wden$, it is shown in Figure 2 (b), where $tptr$ is set to $heursure$, $sorh$ is taken as s, wavelet decomposition level n is 3, the threshold scale ratio of parameter $scal$ is taken as one, wavelet is $sym\,8$ when signal is decomposed. That is to say. $xd = wden(x,'heursure','s','one',3,'sym8')$.

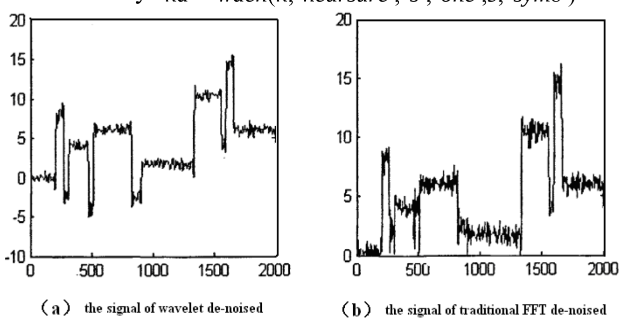

Figure.3 de-noised signal contrast chart

It is shown in Figure.3 that the peak and mutation of useful signal can be well preserved if the signal is de-noised by wavelet transform. If Fourier method is adopted, because the signal concentrates on the low frequency part and the noise distributes in the high-frequency part, although filter is realized by low-pass filter, it can not effective distinguish mutations of the useful signal and high frequency interference that induced by noise. If the low-pass filter is too narrow, there is still a lot of noise when filter is realized, if the low-pass filter is too wide, a part of the useful signal is filtered in the form of noise. Compared with FFT transform, application of wavelet analysis in non stationary signal de-noised has the relatively large advantage. Therefore, the wavelet transform is adopted in the paper.

B. Vibration Data De-noised Process

In water pump running process, the vibration signal is often subjected to various noise and interference, in order to reduce experiment bias of the measured vibration data, and ensure the normal use of the vibration data, it is necessary to de-noised process of vibration data. Water pump vibration signal is often non-stationary signal, the wavelet analysis can simultaneously analyze signal in time frequency domain, so it can effectively distinguish noise and the mutant part of the signal, thus the signal de-noised is achieved.

the pump vibration signal is collected in the form of the normal operation, pedestal looseness and misalignment fault respectively, as is shown in Figure.4, and vibration signal acquisition frequency is 20KHz, the number of sampling points is 2400. Figure 5 is de-noised vibration signal by wavelet transform, the system adopts a threshold de-noised method, the wavelet base is the sym6 wavelet, and the wavelet decomposition level is 4. As can be seen from the graph, the vibration signal collector can well collect vibration signal when water pump is running, the vibration signal after the wavelet de-noised can effectively eliminate high frequency noise.

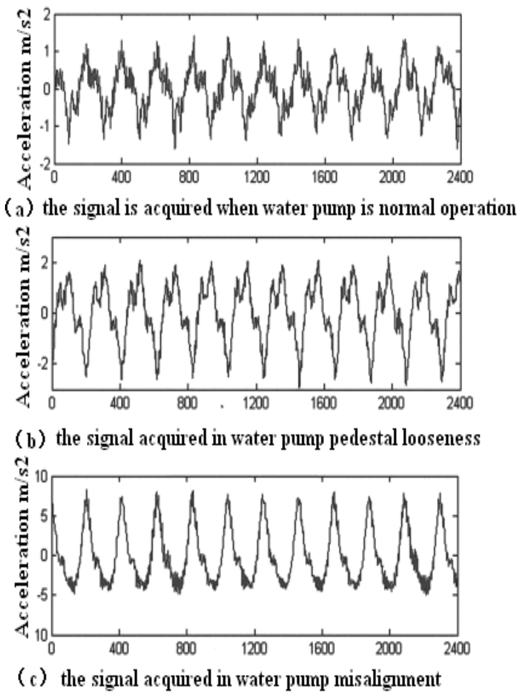

Figure.4 signal acquired before de-noise

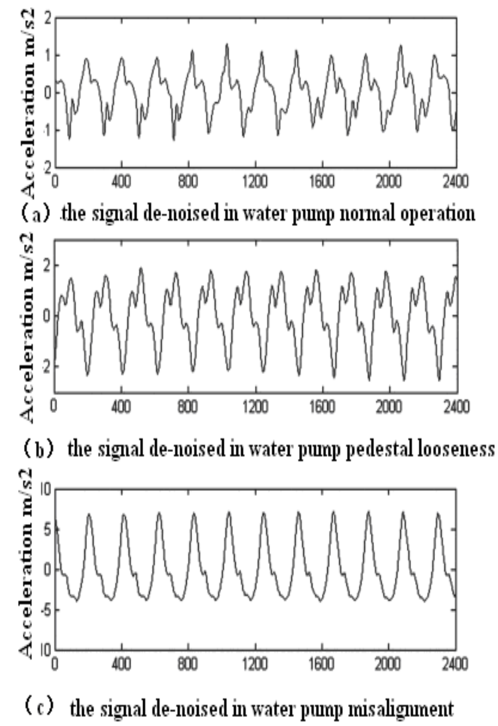

Figure.5 signal acquired after de-noise

IV. VIBRATION FEATURE EXTRACTION AND FAULT MODEL

A Vibration Feature Extraction

In faults diagnosis of water pump, the *Lipschitz* index is very important, and it can be said to a quantitative index of the signal mutation level [4]. The physical significance of *Lipschitz* index is steep corrosion degree of the signal peak, and the degree of faults is more serious, the impact is bigger, then the wave peak of singular point is steeper, the singularity exponent is smaller; conversely, the degree of fault is more less, the impact is smaller, the wave peak of singular point is slower, the singularity exponent is larger. Therefore, the faults and its severity are judged by above, and the quantitative results are given. So we have the important basis of faults feature extraction. By vibration signal singularity analysis, we can get vibration signal singularity distribution as well as important information of the *Lipschitz* index. The relevant vibration parameters information are obtained according to the formula (1) [5], namely, the average value a of the *Lipschitz* index α, the variance s of α, the average time interval Ta of the adjacent two singular points, the time interval variance Ts the adjacent two singular points. In this paper, a, s, Ta, Ts is taken as the pump faults characteristic values.

$$\begin{cases} a = \dfrac{1}{n}\sum_{i=1}^{n} \alpha_i \\ s = \dfrac{1}{n}\sum_{i=1}^{n} (\alpha_i - a)^2 \\ Ta = \dfrac{1}{n-1}\sum_{i=1}^{n-1} t_i \\ Ts = \dfrac{1}{n-1}\sum_{i=1}^{n-1} (t_i - Ta)^2 \end{cases} \quad (1)$$

B Faults Model

In the paper, we study six kinds of working condition of water pump, namely, water pump normal operation, slightly unbalanced, serious imbalance, bearing slight loosening, bearing gross loosening and heating fault and so on. Supposed that fault sets are S1, S2, S3 and S4, and each fault set contains the relevant number of faults. Fault sets are separately determined by the a, s, Ts, Ta. When fault type is St, $S1(St)$ can be obtained by the average value a, $S2(St)$ can be obtained by variance s of a, $S3(St)$ can be obtained by the average time interval Ta of adjacent two singular points, $S4(St)$ can be obtained by the time interval variance Ts of two adjacent singularity, and the fault model can be expressed, it is shown in the formula (2).

$$F(St) = f(S1(St), S2(St), S3(St), S4(St)) \quad (2)$$

When $S1(St)$, $S2(St)$, $S3(St)$ and $S4(St)$ are obtained by the characteristic values a, s, Ts, Ta respectively, the fault model knowledge base must be established according to the fault characteristic values, the fault model is described by the characteristic parameters which can reflect fault state. Therefore, the experiment is done according to various fault types, the $a_{\max}$, $s_{\max}$, $Ts_{\max}$, $Ta_{\max}$ and $a_{\min}$, $s_{\min}$, $Ts_{\min}$, $Ta_{\min}$ are calculated when water pump is in the normal working state and kinds of faults state. If the fault type is St, and fault sets is expressed in the formula (3).

$$\begin{cases} S1(St) \in (a_{\min}(St), a_{\max}(St)) \\ S2(St) \in (s_{\min}(St), s_{\max}(St)) \\ S3(St) \in (Ta_{\min}(St), Ta_{\max}(St)) \\ S4(St) \in (Ts_{\min}(St), Ts_{\max}(St)) \end{cases} \quad (3)$$

The fault characteristic values a, s, Ts, Ta are extracted from the pump vibration signal in real time, and match with each fault set in fault model knowledge base respectively, then we can judge whether the fault characteristic values are in corresponding fault sets or not. If the characteristic value is in corresponding fault sets, and the fault type matching is successful, then the fault type is incorporated into the corresponding sets, another fault types matching do the same work too, all the successful matching fault types are incorporated into the corresponding sets, the corresponding sets are called suspected fault sets that are obtained by the corresponding fault characteristic values judgment. According to this theory, we obtain the following conclusion through many times fault simulation experiments, when the fault type is HR, $a_{\max}$, $s_{\max}$, $Ta_{\max}$, $Ts_{\max}$ and $a_{\min}$, $s_{\min}$, $Ta_{\min}$, $Ts_{\min}$ that are obtained by experiment are 1.1500,0.1600,46.9787,446.5000 and 0.9000,0.0700,40.9825,410.6000 respectively, and the fault sets are shown in formula (4) for normal operation of water pump.

$$\begin{cases} S1(HR) \in (0.9000, 1.1500) \\ S2(HR) \in (0.0700, 0.1600) \\ S3(HR) \in (40.9825, 46.9787) \\ S4(HR) \in (410.6000, 446.5000) \end{cases} \quad (4)$$

When the fault types are UB, water pump slightly unbalanced fault sets are shown in formula (5).

$$\begin{cases} S1(UB) \in (0.7309, 0.7772) \\ S2(UB) \in (0.2175, 0.3025) \\ S3(UB) \in (39.9014, 45.2525) \\ S4(UB) \in (575.0857, 693.8477) \end{cases} \quad (5)$$

When the fault types are UBS, the fault sets are shown in formula (6) when water pump unbalance fault increases.

$$\begin{cases} S1(UBS) \in (1.2011, 1.3565) \\ S2(UBS) \in (0.1454, 0.2053) \\ S3(UBS) \in (36.000, 41.3755) \\ S4(UBS) \in (176.0175, 273.1098) \end{cases} \quad (6)$$

When the fault types are SL, water pump pedestal looseness fault sets are shown in formula (7).

$$\begin{cases} S1(SL) \in (1.3267,1.4161) \\ S2(SL) \in (0.0361,0.1033) \\ S3(SL) \in (37.5574,39.8644) \\ S4(SL) \in (215.1537,300.1526) \end{cases} \tag{7}$$

When the fault types are SLS, fault sets are shown in formula (8) when water pump pedestal looseness fault increases.

$$\begin{cases} S1(SLS) \in (0.6023,0.7642) \\ S2(SLS) \in (0.1038,0.2562) \\ S3(SLS) \in (42.8627,51.9111) \\ S4(SLS) \in (466.0408,573.1625) \end{cases} \tag{8}$$

When the fault types are HT, pump heating fault sets are shown in formula (9).

$$\begin{cases} S1(HT) \in (0.030,0.070) \\ S2(HT) \in (0.004,0.0389) \\ S3(HT) \in (33.30,34.700) \\ S4(HT) \in 126.35,154.12) \end{cases} \tag{9}$$

C Fault Model Matching Algorithm

The fault diagnosis algorithm is shown in Figure.6. First of all, the fault model knowledge base is built up. Simulation experiments are done for different fault types, the fault sets $S1$, $S2$, $S3$ and $S4$ for each fault state calculated respectively, then forming fault model knowledge base. Secondly, the real time fault characteristic values of water pump are extracted. The vibration signal in the pump running state is collected in real-time, and the vibration signal is pre-processed, the fault characteristic values a, s, Ts and Ta are extracted according to singularity analysis of the $Lipschitz$ index. Then the fault model is matched. Water pump fault characteristic values a, s, Ts and Ta match with corresponding fault sets of the fault model knowledge base, and the suspected fault sets $S_1^{'}$, $S_2^{'}$, $S_3^{'}$ and $S_4^{'}$ are obtained. Finally, the fault is diagnosed in an operation state of water pump. The intersection of suspected fault sets $S_1^{'}$, $S_2^{'}$, $S_3^{'}$ and $S_4^{'}$ are done, namely, $F = S_1^{'} \cap S_2^{'} \cap S_3^{'} \cap S_4^{'}$. The results F of fault diagnosis are obtained.

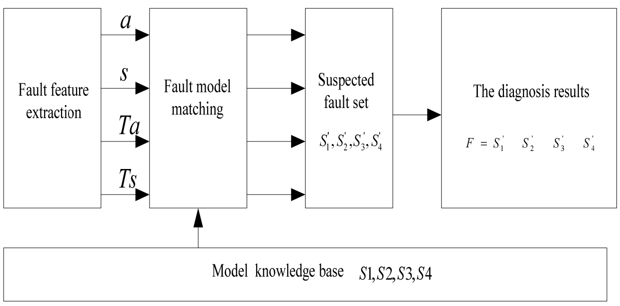

Figure.6. the structure chart fault diagnosis algorithm

V. THE EXPERIMENTAL RESULTS AND CONCLUSION

This experiment adopt is the data acquisition system that is design by our own. Vibration signal acquisition board is shown in figure.6. The vibration signal acquisition system is fixed on water pump, and vibration signal in certain operation condition is collected real-time. The original vibration data that is collected is de-noised by the wavelet transform.

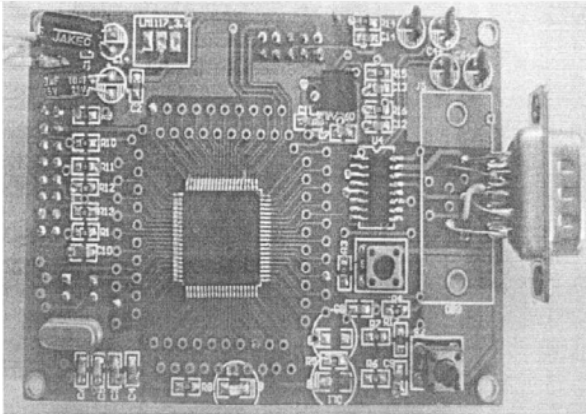

Figure.6 Vibration signal acquisition board

Then water pump vibration signal feature values are extracted, water pump faults are diagnosed by using the established fault model knowledge base and matched algorithm, in order to verify the feasibility of the method for fault diagnosis. the fault characteristic values a, s, Ts, Ta, the suspected fault set $S_1^{'}$, $S_2^{'}$, $S_3^{'}$, $S_4^{'}$ and fault diagnosis results F are given in six kinds of water pump working condition $ST1$, $ST2$, $ST3$, $ST4$, $ST5$ and $ST6$. It is shown in Table 1.

TABLE.1

TYPICAL FAULT DIAGNOSIS ANALYSIS TABLE

Working condition		ST1	ST2	ST3	ST4	ST5	ST5
Fault characteristic value	a	0.9716	0.7352	1.2224	0.8729	1.3746	1.0657
	s	0.2682	0.2693	0.1846	01101	0.0361	0.0101
	Ta	38.9333	44.3774	40.9825	48.6909	39.4483	33.8551
	Ts	313.4192	609.3933	253.8747	511.5264	280.3920	152.7434
suspected fault		$S_1^{'}=\{HR\}$ $S_2^{'}=\{HR,UB\}$ $S_3^{'}=\{HR,UBS,SL\}$ $S_4^{'}=\{HR\}$	$S_1^{'}=\{UB\}$ $S_2^{'}=\{UB\}$ $S_3^{'}=\{UB,SLS\}$ $S_4^{'}=\{UB\}$	$S_1^{'}=\{UBS\}$ $S_2^{'}=\{UBS,SLS\}$ $S_3^{'}=\{HR,UB,UBS\}$ $S_4^{'}=\{UBS,SL\}$	$S_1^{'}=\{SL\}$ $S_2^{'}=\{SL\}$ $S_3^{'}=\{HR,UBS,SL\}$ $S_4^{'}=\{SL\}$	$S_1^{'}=\{SLS\}$ $S_2^{'}=\{SLS\}$ $S_3^{'}=\{SLS\}$ $S_4^{'}=\{SLS\}$	$S_1^{'}=\{HR,HT\}$ $S_2^{'}=\{SL,HT\}$ $S_3^{'}=\{HT\}$ $S_4^{'}=\{HT\}$
The results of fault diagnosis		$F = HR$	$F = UB$	$F = UBS$	$F = SL$	$F = SLS$	$F = HT$

Table 1 is shown that $ST1$, $ST2$, $ST3$, $ST4$, $ST5$ and $ST6$ express water pump operation, water pump running mild imbalance, unbalance aggravate, slightly loose, bearing pedestal looseness fault, heating aggravated in six unknown working state respectively. The diagnosis results show that the method can effectively distinguish the operation state of water pump, and the fault diagnosis of water pump is completed.

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Yongxian Song was born in Xuzhou, on April 1, 1975. He received the B.S. degree in Applied Electronic Technology from Huaihai Institute of Technology, Lianyungang, China, in 1997, and the M.S degree in Control Theory and Control Engineering from Jiangsu university, Zhenjiang, China , in 2006. From 2009 to now, He is studing for Ph.D degree in Control Theory and Control Engineering from Jiangsu University, Zhenjiang, China.

Since 2006, he has beeen a teacher in Huaihai Institute of Technology, Lianyungang, China. His current research interests include signal processing intelligent control, and industrial control.

Kangde Zhao was born in 1986, she received the B.S. degree from Jiangsu university, Zhenjiang, China, in 2006, and the M.S degree in Control Theory and Control Engineering from Jiangsu university, Zhenjiang, China , in 2010.

Yuan Feng was born in Lianyungang, on March 28, 1978. He received the B.S. degree in Computer hardware and application from Huaihai Institute of Technology, Lianyungang, China, in 1999. and the M.S degree in Industrial Control from Nanjing University of Science, Nanjing, China, in 2007. From 1999 to now, he has been a teacher in Huaihai Institute of Technology, Lianyungang, China. His current research interests include signal processing, Computer Control Technology.