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# Research on On-Line Automatic Diagnostic Technology for Scratch Defect of Rolling Element Bearings

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*An on-line automatic diagnostic technology is presented in this paper, based on the simplified vibration model of early scratch defects of rolling element bearings and the analysis of vibration characteristics of early scratch defects. According to characteristics of periodic high frequency natural vibration excited by early scratch defects of the bearing, high frequency resonance technique (HFRT) is adopted for on-line diagnosing in the paper. An algorithm on peak detection of the vibrational energy is used to catch the main frequency of high frequency resonance automatically, denoising technology to improve the signal-to-noise ratio, and automatic identification technology to evaluate defect site of the tested bearing. An on-line automatic diagnostic system for early scratch defects of rolling element bearings, developed based on the above principles, can effectively identify early scratches on outer race, inner race and ball.*

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## NOMENCLATURE

| | |
|---|---|
| $c$ = damping factor | $T$ = period |
| $D$ = diameter | $U$ = modal vectors |
| $d_m$ = pitch diameter | $x$ = displacement |
| $F$ = applied force | $Z$ = number of rolling elements |
| $f$ = frequency | $\alpha$ = contact angle |
| $k$ = stiffness | $\delta$ = impulse function |
| $m$ = mass | $\tau$ = integration constant |
| $n_i$ = rotation speed | $\xi$ = damping ratio |
| $p$ = impact intensity | $\omega_d$ = natural frequency with damping |
| $q$ = generalized coordinate | $\omega$ = natural frequency |

**subscripts**

| | |
|---|---|
| $o$ = outer ring | $d$ = defect |
| $i$ = inner ring | $r$ = radial direction |
| $b$ = rolling element | $s$ = shaft |

## 1. Introduction

Rolling element bearings, as a kind of common assembly units, are widely used in various rotary machineries. With the improvements of material and manufacturing technology and the higher and higher demands on environment protection, especially in household applications and many other areas, the vibration and noise characteristics of rolling element bearing turn into important quality parameters. The early scratch defects generated in bearing manufacturing not only affect vibration level of bearing, but also are the main reason leading to abnormal sounds.

For studying the vibration response of impulse generated by bearing defects, a simplified vibration model named vibration response model of defect was presented based on structural vibration model of bearing by Afshari and Loparo.[1] The vibrations produced by a single defect and multiple defects in a rolling element bearing were studied respectively by Mcfadden and Smith,[2,3] in which impulse excitations of bearing defects were simulated using a train of periodical impulse function. Considering the impacts on bearing vibrations due to different load and impulse wave induced by the defects, an analytical model of bearing system has been proposed by Tandon and Choudhury[4] and Patel et al.[5] to research the frequencies and amplitudes of bearing vibration induced by the defects in different places on rolling elements under radial and axial loads. Although their models and analytical methods were given to analyze the influence of bearing defects on vibration, researches on on-line diagnostic methods suitable for the production process were involved too sketchily.

In actual production process, it requires accuracy, high efficiency and intelligence to diagnose the scratch defects of rolling element bearing. In order to analyze the characteristics of bearing vibration caused by early scratch defects and to seek the diagnostic method suitable for the production process, a simplified vibration model of early scratch defects of rolling element bearing is built. Based on the analysis of vibration characteristics of early scratch defects, an on-line automatic diagnostic technology is presented in this paper.

## 2. Characteristic Analysis on Vibration Caused by Scratch Defects

### 2.1 Vibration model of rolling element bearing

It is assumed that the rotating speed of inner ring is constant and outer ring under a thrust load is stationary. The bearing vibration model considering early scratch defects is simplified as shown in Fig. 1, where $m_i$, $m_o$, and $m_b$ respectively are the masses of inner ring, outer ring and mass of all the rolling elements. The couple between rolling element and inner ring and the couple between rolling element and outer ring are simplified as couples of springs and dampers.[6] Their stiffnesses and damping factors are $k_i$, $k_o$ and $c_i$, $c_o$ respectively as shown in Fig. 1. Thus, a mass-spring-damper system with two degrees of freedom (DOF) could be used to describe the vibration model, and its differential equations are expressed as following

$$\begin{cases} m_o\ddot{x}_o(t)+c_o\dot{x}_o(t)-c_o\dot{x}_b(t)+k_o x_o(t)-k_o x_b(t)=F_o(t)+F_r \\ m_b\ddot{x}_b(t)-c_o\dot{x}_o(t)+(c_o+c_i)\dot{x}_b(t)-k_o x_o(t)+(k_o+k_i)x_b(t)=F_b(t) \end{cases} \tag{1}$$

By solving equations (1), the displacement of outer ring can be expressed as[7]

$$x_o(t)=u_{11}q_1(t)+u_{21}q_2(t) \tag{2}$$

Where

$$q_j(t)=\frac{1}{\omega_{dj}}\int_0^t(\vec{U}_j^{\,T}\vec{F}(\tau))e^{-\xi_j\omega_j(t-\tau)}\sin\omega_{dj}(t-\tau)d\tau \quad (j=1,2) \tag{3}$$

$$\omega_{dj}=\omega_j\sqrt{1\text{-}\xi_j^{\,2}} \quad (j=1,2) \tag{4}$$

$$\vec{U}_j=\begin{bmatrix}u_{j1} & u_{j2}\end{bmatrix}^T \quad (j=1,2) \tag{5}$$

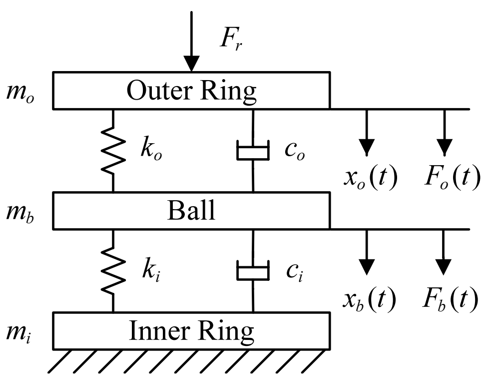



Fig. 1 Vibration model of rolling element bearing

$$\vec{F}(t)=\begin{bmatrix}F_o(t) & F_b(t)\end{bmatrix}^T \tag{6}$$

### 2.2 Simulation of vibration under scratch defects and its characteristics analysis

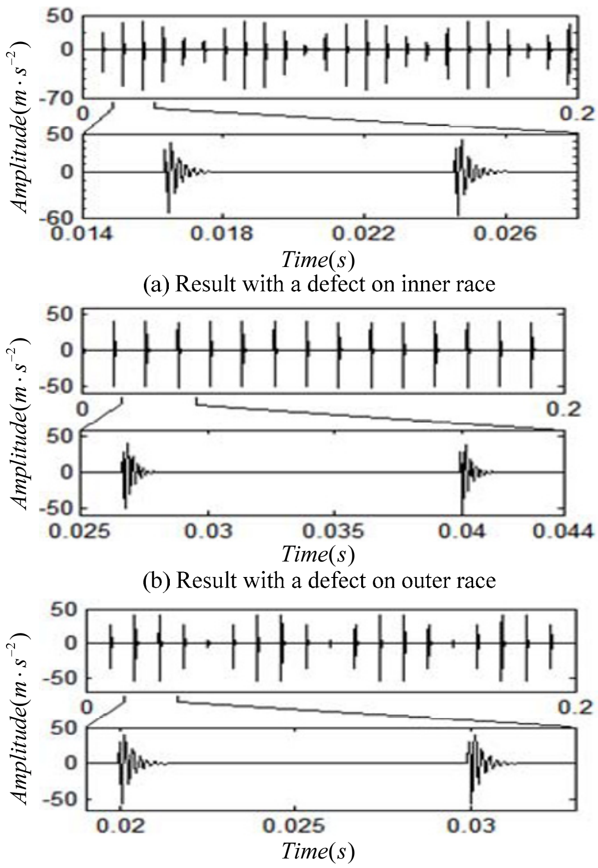
The periodical impact produced by defects can be considered as a series of impulse function with the period of $T$, which is expressed as

$$F(t)=\sum_{j=0}^{+\infty}p_j\delta(t-jT-t_0) \qquad (j=0,1,2\cdots) \tag{7}$$

Where $p_j$ is the impulse amplitude simulating the defect and it depends on severity of defect and relative position between defect and sensor; $T$ is period of the defect appearance while bearing rotating and it is determined by the position of defect and the shaft speed, and $t_0$ is the initial phase.

Simulation signals of bearing vibration caused by scratch defects on inner race, outer race and one ball are shown in Fig. 2.

According to the results, the vibration characteristics of the bearing with early scratch defects can be obtained as following. The abnormal vibration generated by the defects is a kind of periodic damped oscillation with larger-amplitude and decaying waveforms. The frequency of the damping wave is related to the ball passing frequency corresponding to the defect. Scratch defect excites high frequency natural vibration of the bearing. The damping waves excited by defect on the inner race or one ball are amplitude modulated, and the waves excited by defect on outer race are general of equal amplitude.




(a) Result with a defect on inner race

(b) Result with a defect on outer race

(c) Result with a defect on ball

Fig. 2 Simulation signals of bearing vibration

## 3. On-Line Diagnostic Technology for Scratch Defect

### 3.1 Demodulation technique of high-frequency resonance

Scratch defect excites high frequency natural vibration of bearing and the vibration signals are interfered by low-frequency noise commonly, so that it easily causes error in judgment to diagnose the scratch defects directly by means of direct spectral analysis. High-frequency resonance technique (HFRT)[8] or envelop detection is an important signal processing technique, which is helpful in identification of bearing defects by extracting characteristic defect frequencies.[9,10] Its process is shown in Fig. 3.

The vibration signals generated by defects, which contain high frequency resonance components, are collected by transducer. Firstly, the signals are bandpass-filtered around one of the resonance frequencies to separate this high frequency natural vibration from original signals. Then the bandpass-filtered signal is demodulated by an envelope demodulation detector, Hilbert transform for example, to eliminate its resonance frequency, thus enveloped signal contained defect information only can be obtained. Therefore, vibration signal generated by defect are demodulated. The characteristic defect frequencies will be got in spectrum analysis of the enveloped signal.

### 3.2 Intelligent diagnostic technique

#### 3.2.1 Characteristic defect frequencies

Each bearing element has a characteristic rotational frequency. If a certain bearing element exists a defect, vibrational energy at this element's rotational frequency may increase. These characteristic defect frequencies can be calculated from kinematic parameters such as the geometry of the bearing and its rotational speed.[10] For a bearing with a stationary outer race, these frequencies are given by the following expressions.

Outer race defect frequency:

$$f_{od} = \frac{Zf_s}{2}\left(1 - \frac{D_b}{d_m}\cos\alpha\right) \tag{8}$$

Inner race defect frequency:

$$f_{id} = \frac{Zf_s}{2}\left(1 + \frac{D_b}{d_m}\cos\alpha\right) \tag{9}$$

Rolling element defect frequency:

$$f_{bd} = f_s \frac{d_m}{D_b}\left(1 - \frac{D_b^{\,2}}{d_m^{\,2}}\cos^2\alpha\right) \tag{10}$$

#### 3.2.2 Automatic identification of resonance frequency

When there is a scratch defect in rolling element bearing, the high frequency natural vibration will be excited by impact generated by the defect. As a result, the energy of signal in the frequency range centered on this natural vibration frequency will be enhanced. For different type of bearings or different operating environments, there will be great difference in the spectral distribution of bearing vibration signals, see the dotted line shown in Fig. 4.

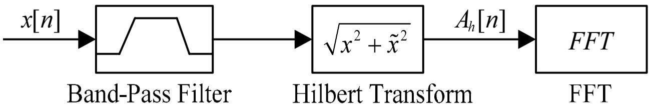


Fig. 3 The process of HFRT

To determine the center frequency of band-pass filter in HFRT, an algorithm on peak detection of the vibrational energy is adopted in this paper. The frequency range from frequency $f_1$ to $f_2$ containing natural vibration frequency is automatic selected to get the main frequency of high frequency resonance. The algorithm is given by the following expression

$$f_0 = \max(X(f)) \qquad f \in (f_1, f_2) \tag{11}$$

Where $f_0$ is the main frequency of high frequency resonance, i.e., the center frequency of band-pass filter, $f_1$, $f_2$ are the bottom and top limitations of analytical frequency range respectively, which are set according to the actual situation.

#### 3.2.3 Improvement of the signal-to-noise ratio of defect frequency

After envelope demodulating, the high frequency components of the vibration signals are filtered and only low-frequency components containing defect frequencies, which are usually less than 500 Hz, are left.[10] Therefore, low-frequency range in envelope spectrum getting rid of zero frequency component is selected to improve the signal-to-noise ratio, shown in Fig. 5.

Vibration and noise will be generated definitely when bearing is rotating, and all kinds of characteristic frequency components will be occurred in vibration signals. So it is unable to confirm the existence of defect in bearing simply when some characteristic frequency component exists in vibration spectrum. Moreover,

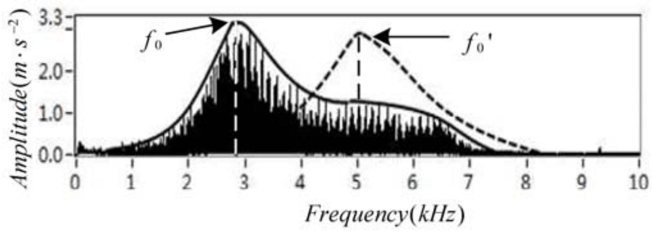


Fig. 4 Spectral distribution of bearing vibration signals

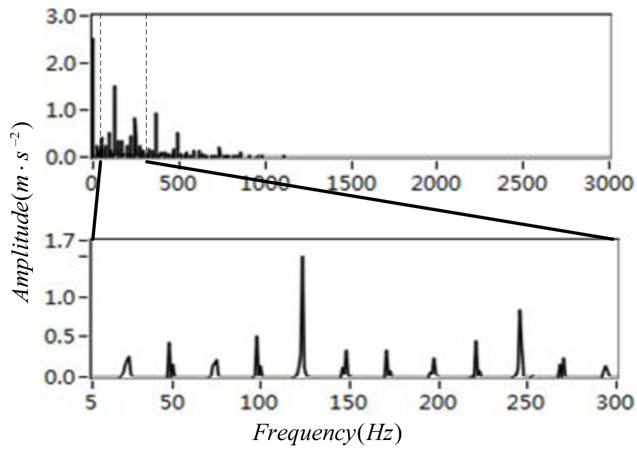


Fig. 5 Improvement of signal to noise ratio

because of the effect of environment noise, it easily causes erroneous judgment by using amplitude as the judgment standard. The ratio of amplitude and root-mean-square (RMS) in envelope spectrum is adopted as the defect level in this paper. Meanwhile, the mean value of defect levels in both defect frequency and its double is used as the judgment standard to improve signal to noise ratio, which can be expressed as following

$$sn = \frac{1}{2}\left(\frac{A_{d1}}{RMS(f)} + \frac{A_{d2}}{RMS(f)}\right) \qquad f \in (5Hz, 300Hz) \tag{12}$$

Where $sn$ is the final defect level of defect frequency, $A_{d1}$ and $A_{d2}$ are the amplitude in envelope spectrum in defect frequency and its double respectively.

### 3.2.4 Automatic decision of the scratch defect site

Defects site of rolling element bearing can be detected using computer automatically by identifying the defect level in the characteristic frequency of its rolling element. In practice, these characteristic defect frequencies may be slightly different from the calculated values because of the existence of slipping and changing of rotating speed when bearing is revolving. Taking scratch defect on outer race for example, the actual envelope spectrum is shown in Fig. 6. It can be seen that the calculated values $f_{od}$ and $2f_{od}$ are slightly different from the frequencies corresponding to the maximum of spectrum.

In this paper, the maximum amplitudes in the ranges of bandwidths $f_{w1}$ and $f_{w2}$ as shown in Fig. 6, which are respectively centered on the theoretical characteristic defect frequency and its double, are adopted as the amplitudes of actual defect frequency and its double for calculating the defect levels as following expressions.

$$A_{d1} = \max(X(f)) \qquad f \in (f_{od} - 0.5f_{w1}, f_{od} + 0.5f_{w1}) \tag{13}$$

$$A_{d2} = \max(X(f)) \qquad f \in (2f_{od} - 0.5f_{w2}, 2f_{od} + 0.5f_{w2}) \tag{14}$$

According to the experimental vibration data of both normal bearings and bearings with scratch defects on inner race, outer race or one ball, the thresholds of defect level corresponding to each kind of scratch defect are set respectively. The tested bearing will be adjudged a defected bearing, if its defect level, $sn$, is higher than the threshold.

## 4. On-Line Automatic Diagnostic System

### 4.1 Mechanical system

Structure of the mechanical system is shown in Fig. 7. The

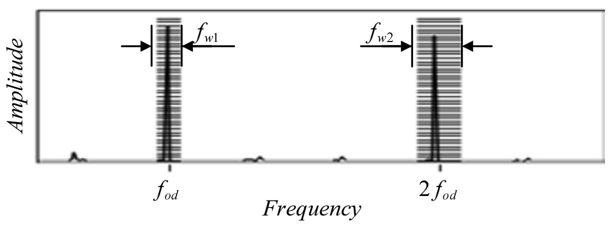



Fig. 6 Automatic decision of the defect levels

automatic machinery delivering the tested bearing in this system mainly consists of four parts, i.e. the preset mechanism, the measuring mechanism, the sorting mechanism and the feeding mechanism. After a tested bearing is delivered to the system and is detected by the sensor, it should implement such actions, in turn, as elevating, positioning, two times measuring, turning over and sorting of the measured bearings. Then the tested bearings are separated into two parts according to the measured results whether or not the tested bearings are qualified. Only qualified products can go to the next process.

### 4.2 Hardwares of electrical system

Structure of hardwares mainly contains vibration detection system of industrial personal computer (IPC) and actions control system of PLC, which is illustrated in Fig. 8. During vibration detection, the radial vibration signal on one point of bearing's outer ring is collected by the piezoelectric acceleration sensor, then amplified by a charge amplifier and converted to voltage signal. The voltage signal of the vibration is converted by an A/D converter and then is sent to IPC for its further processing. In actions of measuring procedure, the positions and states of the tested bearings are detected respectively by corresponding sensors, and the actions of mechanical system are implemented by pneumatic devices controlled by PLC.

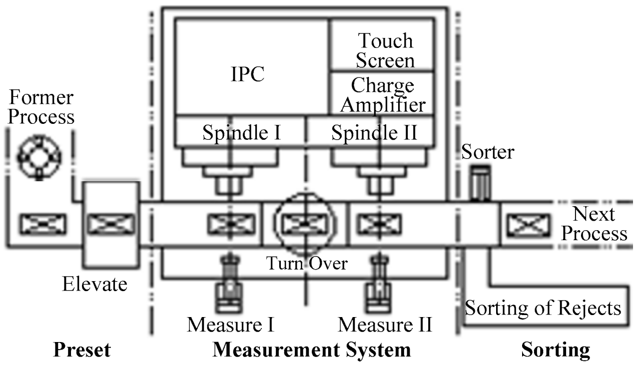



Fig. 7 Structure chart of mechanical system

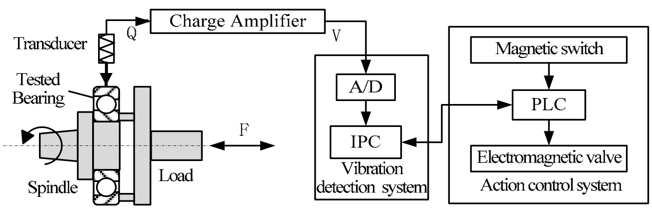



Fig. 8 Hardware structure chart of electrical system

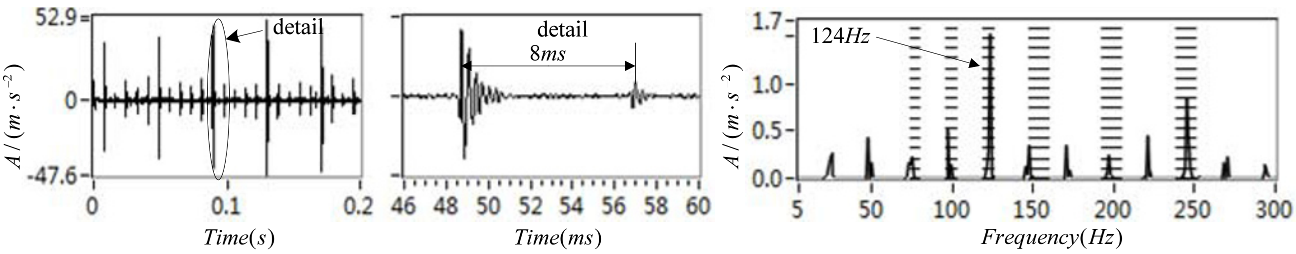
Table 1 Parameters of 63/28-2RZ

| Items | Value | Units |
|---|---|---|
| Inner ring diameter $D_i$ | 28 | mm |
| Outer ring diameter $D_o$ | 68 | mm |
| Ball diameter $D_b$ | 11.509 | mm |
| Pitch diameter $d_m$ | 48.5 | mm |
| Contact angle $\alpha$ | 0.274 | rad |
| Number of balls $Z$ | 8 | |
| Rotational speed $n_i$ | 1492 | rpm |

## 5. Results

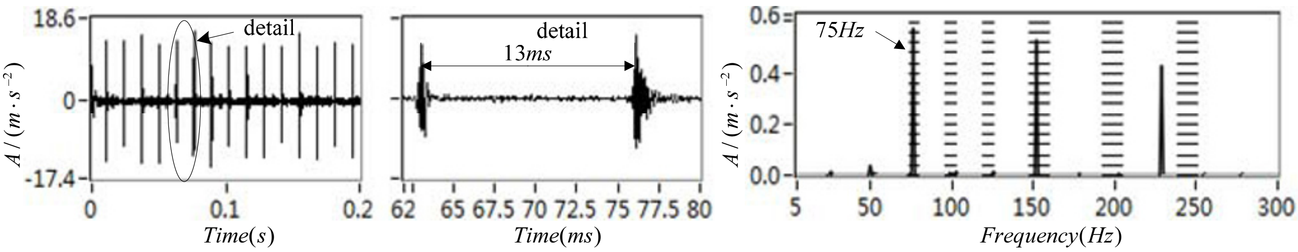
Deep groove ball bearings with the type of 63/28-2RZ are used as the test bearings and their parameters are shown in Table 1. To verify the above study, three bearings with scratch defect introduced by the technique of scratching were examined. The vibration signals in time domain and their envelope spectrums of tested bearings, with the width of scratch defects of 65μm, 70μm and 70μm respectively located on inner race, outer race and one ball, are given in Figs. 9, 10, and 11 respectively. The dash areas in the envelope spectrums are corresponding to the characteristic defect frequencies range of the inner race, outer race, ball, and their double frequencies range respectively.

From the vibration signals in time domain, it is obvious that the abnormal vibration generated by the early scratch defect of bearing is a series of periodic damped oscillation waveforms. And the scratch defects excite high frequency natural vibration of bearing. The frequency of occurrences of the damping waves is basically equal to the ball passing frequency corresponding to the defect. The phenomenon of amplitude modulation occurs in the vibration signal of bearing with defect on inner race, while the amplitudes of damping waves generated by defect on outer race are not so much change, which are coincide with the theoretical analysis. The phenomenon of amplitude modulation is not clear in vibration signal of bearing with defect on one ball because the defect on ball enters into and leaves the contact zone indefinitely as the bearing is rotating. But the defect



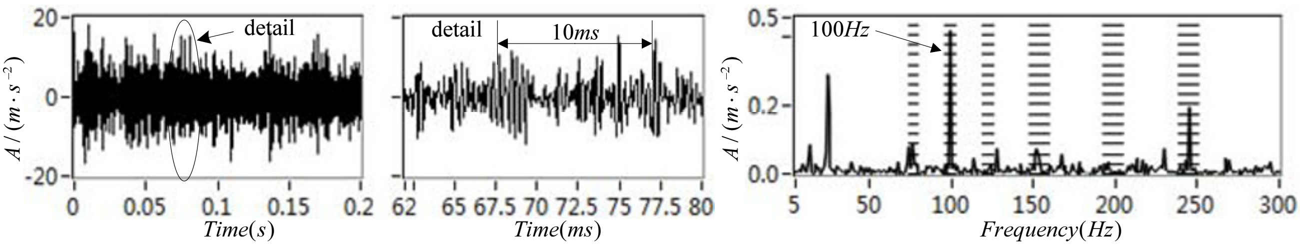
(a) Signal in time domain and its detailed view (b) Spectrum of envelop signal

Fig. 9 Vibration signals of bearing with the width of scratch defect of 65μm located on inner race



(a) Signal in time domain and its detailed view (b) Spectrum of envelop signal

Fig. 10 Vibration signals of bearing with the width of scratch defect of 70μm located on outer race



(a) Signal in time domain and its detailed view (b) Spectrum of envelop signal

Fig. 11 Vibration signals of bearing with the width of scratch defect of 70μm located on one ball

Table 2 Main parameters in on-line diagnostic system

| Items | Threshold of | | | $f_{w1}$ | $f_{w2}$ |
|---|---|---|---|---|---|
| | $sn_i$ | $sn_o$ | $sn_b$ | | |
| Value | 7 | 7 | 5 | 6 | 12 |

Table 3 Results of diagnosis to bearings with scratch defects

| Defect Site | Defect Frequencies (Hz) | | | $sn_i$ | $sn_o$ | $sn_b$ | Vibration Signals |
|---|---|---|---|---|---|---|---|
| | Theoretical Values | Actual Values | Errors (%) | | | | |
| Scratch on inner race | 122.2 | 124 | 1.47 | 9.6 | 2.2 | 3.0 | Fig. 9 |
| Scratch on outer race | 76.7 | 75 | 2.22 | 0.3 | 9.9 | 0.3 | Fig. 10 |
| Scratch on one ball | 99.3 | 100 | 0.70 | 2.9 | 2.1 | 5.9 | Fig. 11 |

level in rolling element defect frequency is so clear in envelope spectrum of vibration signals that the tested bearing could be judged with defect on one ball, see Fig. 11.

The main parameters set in the on-line diagnostic system are shown in Table 2. The actual defect frequencies and defect levels of inner race, outer race and ball can be obtained from the envelope spectrums, and make the decision whether some scratch defects are in the tested bearing or not. The diagnosis results to scratch defects are shown in Table 3. It shows that the actual defect frequencies are close to the theoretical values with the errors in the range of 3%. The defect levels can be calculated correctly for the given bandwidths $f_{w1}$ and $f_{w2}$. It indicates that the automatic diagnostic system can effectively identify early scratches on outer race, inner race and ball of rolling element bearing.

## 6. Conclusions

The following conclusions can be drawn from the experimental results and analysis.

(1) For the vibration of a running bearing, the scratch defects on its rolling elements can be considered as impulse source with the period of $T$ related to the defects.

(2) Scratch defects excite high frequency natural vibration of the bearing. And the abnormal vibration generated by the defects is a kind of periodic damped oscillation with larger-amplitude and decaying waveforms.

(3) High-frequency resonance technique is helpful in identification of bearing defects by extracting characteristic defect frequencies.

(4) The center frequency of band-pass filter in HFRT could be determined simply and effectively by peak detection algorithm of vibration energy given in this paper.

(5) The on-line automatic diagnostic system for early scratch defects of rolling element bearing developed in this paper could join up with a bearing assembly line to test vibrations of assembled bearings and identify early scratches on outer race, inner race and ball of rolling element bearing. It could also be used for vibration analysis off-line.

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