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The Identification of Shaft Current Induced Defects on Rolling Bearings in Wind Turbine Generators

Long Li, Guangbin Wang, Wenhui Deng

Hunan Provincial Key Laboratory of Health Maintenance for Mechanical Equipment

Hunan University of Science & Technology

Xiangtan, China

jxxwgb@126.com, longlivip@126.com

Xiaoli Tang, Fengshou Gu, Andrew D. Ball

Center for efficiency and Performance Engineering

University of Huddersfield

Huddersfield, UK

***Abstract*—Rolling bearings are an important part of wind turbine systems. Shaft current induced damages are one of the main causes for bearing failures, which lead to considerable operation loss of wind turbine plants. In this paper, the characteristics of shaft current damages and their induced vibration responses are studied analytically. Then it suggests to use an emerging Modulation Signal Bispectrum (MSB) to detect and diagnose the incipient defects as MSB can suppress various noise and provide a sparse result that integrates particularly the fault modulator and the structural resonance carrier to highlight the fault effect. Finally, the detection and diagnosis results based on both simulated signals and experimental signals show the outstanding performance of MSB analysis in detecting common bearing faults. Especially, it can achieve a straightforward differentiation between the fatigue pitting defects and shaft current damages, whereas conventional envelope analysis cannot provide a separation between these two types.**

Keywords-shaft current; bearing fault diagnosis, envelope spectrum; MSB

I. INTRODUCTION

Rolling bearings are an important part of wind turbine systems. The shaft current is the main root of bearings damage of wind turbines. When a rolling bearing fails, the vibration signal from mechanical faults is often expressed as a certain form of the modulation. Fault characteristics can be extracted effectively by demodulating the signal obtained from the mechanical system with faults. Therefore, the signal demodulation methods have been widely applied in the rolling bearing fault diagnosis[1-4]. Nonetheless, the common diagnostic analysis methods on rolling bearing have some deficiencies. In recent years, the shaft current of bearings on the motor bearing has been studied by many scholars, most of whom research shaft current causes and preventive measures, such as Guanhao Yan et al. Based on the viewpoint of shaft current producing theory, the mechanism and defects induced by the shaft current from variable-frequency motors are analysed, and the useful testing analysis method of shaft current is introduced. At last, the measures of restraining power supply harmonic, installing carbon brush and applying spike voltage absorber (SVA) are proposed to prevent variable-frequency motor from destroying[5]. Fanglin Deng et al. analysed the generation mechanism of common mode voltage, which presented a high frequency equivalent circuit model of DFIG, then analysed the characteristics of various bearing currents and their flow paths and summarized their preventive measures and basic design principles[6]. Some scholars investigated the signals of the shaft current damage. For example, Aurelien Prudhom proposed a time-frequency vibration analysis method for the detection of motor damages caused by bearing currents[7]. Lianshen Zhang applied the spectral analysis in shaft current fault of rolling bearings[8]. Chenggang Hua explored the damage signal of shaft current through the spectral analysis of the online vibration monitoring system[9].

Although there are many methods presented on bearing fault diagnosis, few researches devote to the damage identification of bearing shaft currents. In this paper, the MSB method is used to identify the fault signal of the shaft current, which can be distinguished from pitting faults, and the purpose of fault type identification is achieved. Gu et al. named this method as the Modulation Signal Bispectrum (MSB) analysis and achieved fault diagnosis of downstream mechanical equipment using electrical motor current signals in 2011 [10]. After that, their team continues to deeply study and analyse the method to achieve a series of achievements [11-15].

II. THE DAMAGE MECHANISMS DUE TO SHAFT CURRENT

Under the condition of normal operation of wind turbines, there is a lubricating oil film between the rolling elements and raceways on the main shaft of the wind turbine. Not only does the oil film reduce fraction but also plays a role in electric insulation. Due to the PWM modulation technology of the transducer, there is a common mode voltage at the central point of the motor inner winding. And the common mode voltage can produce shaft voltage between the inner and outer rings of the bearing. This voltage can generate discharge when the potential difference between the inner and the outer rings of bearing is over the breakdown voltage formalised by oil film.

During the discharge process, the breakdown of bearing oil film produces shaft current between raceways, which is normally called shaft current (SC). As a result of SC, electrochemical corrosion occurs on the surface of raceways and rolling elements. This in turn leads to poorer lubrication performance and high temperature. Eventually, there is a number of tiny electrical corrosion pitting on the Hertz contact surface of the raceway, which exhibit as the pitting damage at early stages.

Considering the electrical characteristics of the bearing, the pitting caused by current damage is related to the size of the current, voltage threshold of the oil film and the Hertz contact area or radial load. The relationship between the bearing equivalent resistance [16] and the number of pitting can be predicted based on the following equation.

$$R_B = Rc\left[1+\left(N\beta\right)^{-\frac{1}{2}}\right] \tag{1}$$

According to the physical relationship among the voltage threshold U_b of the bearing lubricating oil film, the equivalent resistance R_B of the bearing and the bearing current I_b, the number of the pitting of bearing current damage can be inferred from the following equation.

$$N = \frac{I_c{}^2 R_c{}^2}{\beta\left(U_b - I_b R_c\right)^2} \tag{2}$$

where the R_c is shown in the following equation.

$$R_c = \frac{\sqrt{\pi}}{2}\rho A^{-\frac{1}{2}} \tag{3}$$

where, ρ is electrical conductivity, U_b is the voltage threshold of breakdown oil film, bearing contact type parameter is point contact $\beta = 0.5$ [17].

From the microscopic perspective, the raceways and element surfaces of bearings have tiny waviness and micro-asperities due to the machining process in which vibration is inevitable. The waviness of the bearing race surface will affect the thickness of the bearing oil film [18], and the corrugated part of the oil film will become thinner. When the shaft voltage breakthrough the film threshold voltage, the bearing current will be generated between the two raceways. At the same time, the waviness will continue to expand along the width of the raceway because the rolling elements have a certain axial oscillation. Specifically, the combined effect of the constant action of the shaft current and mechanical load to the bearing raceway will lead to the phenomena of the washboard corrugated groove, which will start at the loaded zone and expand to other regions of the raceways.

Based on this understanding, it can be deduced that shaft current defects at early stages can produce mechanical impacts in a similar way with that of surface fatigue defects. They both appear with small raceway defects localised in the load zone. Moreover, their significant responses are usually resulted from a modulation coupling between the impacts and system structure resonances. Therefore, it is possible to detect and diagnose the shaft current defects through commonly used vibration methods such as envelope analysis and High Frequency Resonance Technique (HFRT).

III. FAULT IDENTIFICATION METHOD BASED ON MSB

Because the vibration responses of bearing defects at early stages are tiny and often submerged in noise, effective analysis should be used to achieve accurate detection.

A. *Definition of MSB*

According to the references [10-15], MSB is an effective demodulation technique and demonstrated to be able to detect bearing faults under heavy noise influences, Based on Fourier transform $X(f)$ of a vibration signal x, MSB is defined as the following equation.

$$B_{MS}\left(f_c, f_x\right) = E\left\langle X\left(f_c+f_x\right) X\left(f_c-f_x\right) X^*\left(f_c\right) X^*\left(f_c\right)\right\rangle \tag{4}$$

where, f_c is the carrier frequency which can be the frequency of the resonance, and f_x is the modulating frequency which can be the bearing characteristic frequencies. The magnitude and phase of MSB can be expressed as the following equation.

$$A_{MS}\left(f_c, f_x\right) = E\left\langle \left|X\left(f_c+f_x\right)\right|\left|X\left(f_c-f_x\right)\right|\left|X^*\left(f_c\right)\right|\left|X^*\left(f_c\right)\right|\right\rangle \tag{5}$$

$$\varphi_{MS}\left(f_c, f_x\right) = \varphi\left(f_c+f_x\right) + \varphi\left(f_c-f_x\right) - \left|\varphi\left(f_c\right)\right| - \left|\varphi\left(f_c\right)\right| \tag{6}$$

Obviously, the magnitudes at $f_c - f_x$ and $f_c + f_x$ in (5) are used for measuring the nonlinear effects of modulation signal components. If there are nonlinearity effects on them, the bispectral peak will appear. Simultaneously, the signal content with random distribution the magnitude of MSB is close to nil as these components are not coupled. By this means, wideband noise in bearing vibration signals can be suppressed effectively. So the discrete components relating modulations can be obtained more accurately.

B. *MSB Evaluation based on Simulation Signal*

When a rolling bearing has local defects, vibration signals from mechanical faults are often expressed as a certain form of modulation. Usually, the actual fault vibration signal is the superposition of a number of amplitude and frequency modulation signals. A fault signal is assumed as follows:

$$x(t) = h(t) * u(t) + n(t) \tag{7}$$

where, $h(t)$ is the impulse response containing the information of system resonance, $u(t)$ is the periodic impacts at fault frequency and $n(t)$ is the white noise. The fault frequency is $f_x = f_f = 70$ Hz and the carrier frequency is $f_c = 1000$ Hz. Additionally, high level white noise is added to the signal, which results in a -25 dB Signal to Noise Ratio (SNR) to examine the performance of MSB in detecting the fault when it is incipient. The time domain waveform and corresponding spectrum are shown in Figure 1. The noise added signal show no chance to find the modulation feature. The spectrum exhibit certain features of modulation but it is difficult to identify the modulating frequency as the spectral lines are very redundant and many of them are buried by the background noise. Moreover, as shown in the magnified plots, the spectrum amplitudes show clear differences from the noise-free one, which can cause incorrect diagnosis of the fault severity.

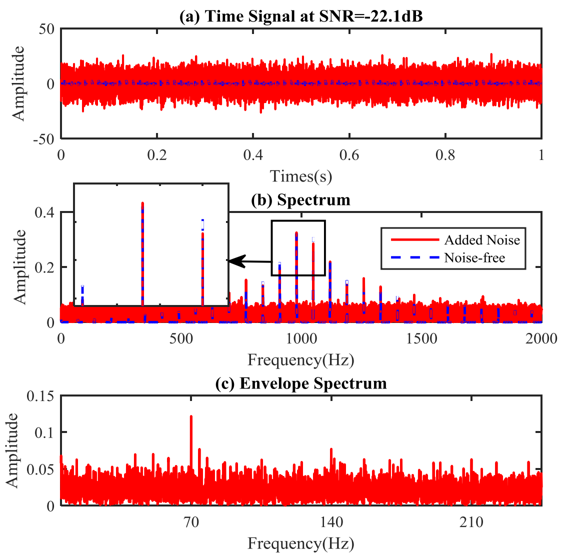


Figure 1. Time domain waveform and spectrum

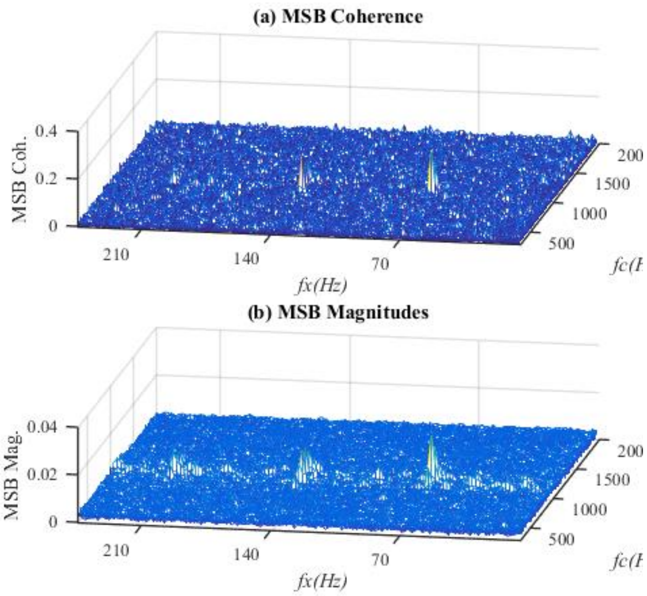


Figure 2. MSB versus conventional envelope

Because of the high level noise or the tiny effect of the fault, the conventional envelope spectrum in Figure 1 (c) also fails in separating the fault signal.

However, MSB results in Figure 2 show several distinctive peaks in the bifrequency plane, making it easy to correlate the peaks with the frequencies of interests. Particularly, either MSB coherence peaks in Figure 2 (a) or MSB magnitude peaks in Figure 2 (b) can indicate clearly the modulation effect between the fault frequency at 70Hz including its harmonics and the resonance at 1000Hz, and hence achieve the fault detection. MSB magnitudes can be used for fault severity diagnosis as its peaks are much less influenced by the noise whereas MSB coherence peaks are more influenced by noise and often an indication of the degree of noise contamination.

Based on these results, it can be concluded that MSB analysis outperforms conventional spectrum and envelope analysis in that it shows a clean or sparse results by integrating the modulating components and carrier components along with the high performance of noise suppression.

IV. Current Damage Identification of Wind Turbine

A. Experimental Method

According to the mechanism of the shaft current formalisation in a large wind turbine, a test bench is designed to simulate the working condition of bearings suffered from the shaft current erosions. The test rig consists of the shaft current generator, the load device, the support device etc. The test bearing model in these experiments is 6205EKA, of which the specific parameters are listed in TABLE I.

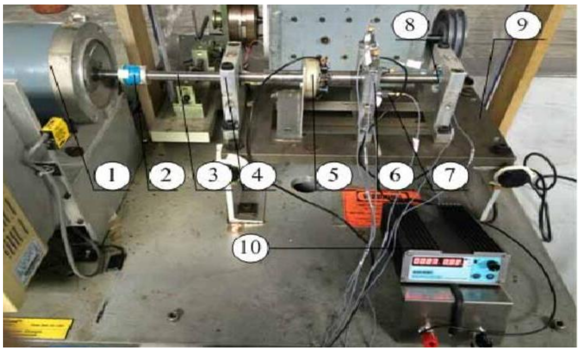
TABLE I. Specifications

Elements	***Values***
Inner diameter	25 mm
Outer diameter	52 mm
Rolling body diameter Shaft	7.925 mm
Pitch circle diameter	39 mm
Rolling element number	9
Rotational speed f_r	20Hz
Output voltage	2.5V

As proposed in the second section, the bearing defects corroded by the shaft current were obtained successfully after this bearing runs long time at a simulated condition and the pattern of the ‘washboard’ corrugated groove is shown in Figure 4. And fatigue pitting bearing is shown in Figure 5.

B. Data Analysis

The signal acquisition is based on a B&K PULSE data acquisition system, consisting of a data acquisition card, vibration accelerometers and acquisition software. The vibration sensors are installed in the three directions of the test bearing: lateral, longitudinal and radial directions. Data are logged for 10 seconds with the sampling frequency of 8192Hz at the motor speed of 1200rpm. The experiments based on three bearings with the condition of health, fatigue pitting and electric current damage were carried out to acquire the vibration signals. Based on the specifications of the bearing listed in TABLE I, theoretical fault frequency of the outer ring is 71.7Hz.



① Motor ② Insulated coupling ③ Main shaft

④ Bearing Support ⑤ Shaft current load device

⑥ Test bearing ⑦ Accelerometer ⑧ Insulated bearing

⑨ Test bed ⑩ Shaft current generator

Figure 3. Test Rig

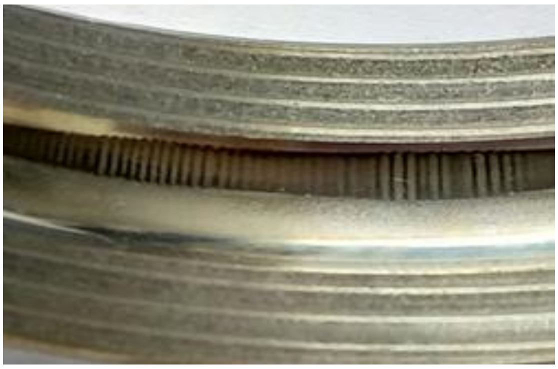


Figure 4. Electric damage bearing

Figure 5. Fatigue pitting bearing

The time domain waveform of the normal bearing, pitting fault bearing and electric damage bearing are shown in Figure respectively. It is obvious that the amplitude of electric damage bearing is significantly higher than those of the normal bearing and pitting bearing. While the amplitudes of the pitting bearing and the normal bearing are very similar. So this cannot determine whether there have been damages or not on the bearings. Especially, it is not possible to accurately diagnose if the changes of the signal is from the bearing or other components because these signals exhibit highly random fluctuations and provide little information of bearing characteristic frequencies.

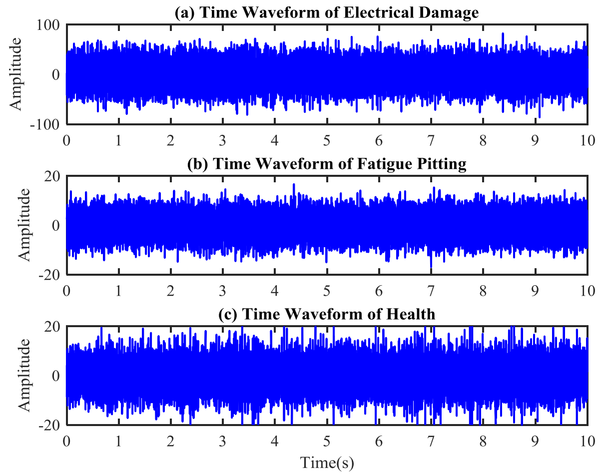


Figure 6. Time domain waveform

The frequency domain analysis is shown in Figure and the spectra of three cases shows the shift of the carrier frequencies in the high frequency band but the spectrum analysis is unable to detect the faults as it is hard to identify the components relating to the characteristic frequencies.

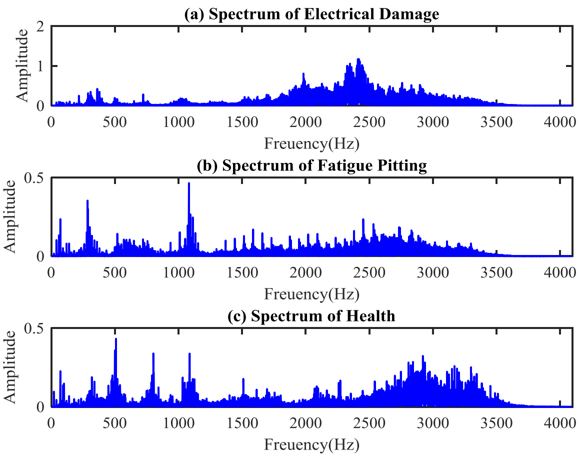


Figure 7. Amplitude spectrum

Hence, envelope analysis is carried out to tackle signals from the normal, fatigue pitting, and electric damage bearings. Figure (a) and (b) demonstrate that the fault characteristics of the two fault cases are obvious and additionally, the fault frequency amplitude of the vibration signal from the case of electric current damage bearing is higher than that of fatigue pitting one, which indicates the fault severity induced by electric damage is more serious. For the health bearing, only the rotating frequency and the corresponding harmonics are acquired by the envelope analysis. Although the envelope spectrum can identify the faults, the envelope analysis is not very sufficient to different the difference between the two faulty cases.

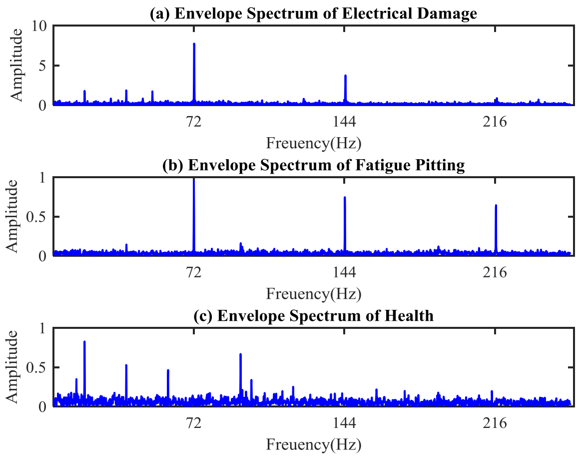


Figure 8. Envelope spectrum

MSB analysis is applied to the time domain signals, and then the results of MSB coherence and magnitudes are shown in Figure and Figure respectively. It can be seen that both MSB coherence and magnitudes have only several peaks are significant. Particularly, they highlight not only the occurrence of the outer race fault but also the resonant frequencies associating with the bearing structures, providing more information to make difference between different cases..

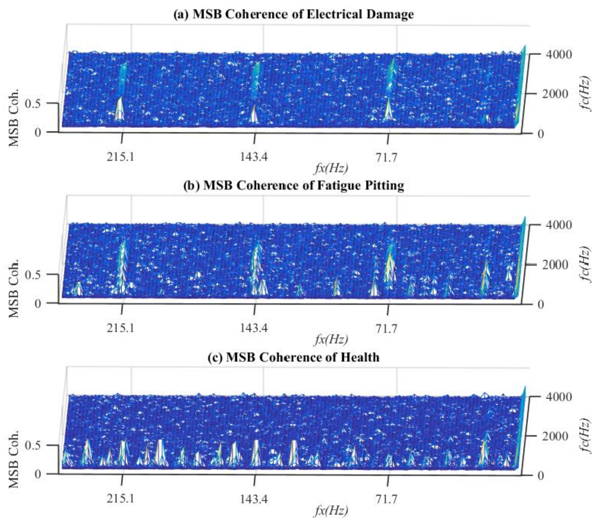


Figure 9. MSB coherence of vibration signals for three cases

As illustrated in Figure and Figure , MSB results allows the fundamental fault frequency and its second and third harmonic to be extracted, which confirms the occurrence of the local faults without any doubt.

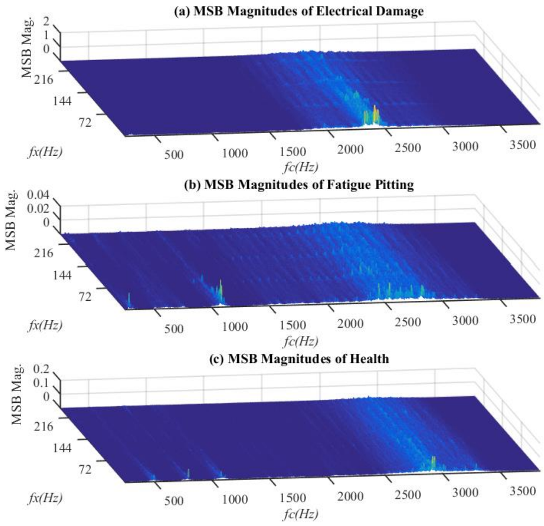


Figure 10. MSB magnitudes of vibration signals for three cases

Moreover, Figure shows that the fault features of three cases are extracted and the carrier frequencies of three cases are different even though the test bearings are the same model. The natural frequencies of the normal bearing is around 2,800Hz while the pitting bearing is at 1,100Hz and 2,600Hz, and electric damage bearing focuses on 2,400Hz. MSB magnitudes, integrating the modulating components and carrier components, shows a clean and sparse spectrum to highlight the fault signature and the bearing system resonant frequencies. The faults induced by electric damage and fatigue affect the dynamics of the bearing system, which leads to the variation of the frequency response function. Combining the fault signatures and the shift of the natural frequencies, MSB is able to identify the fault origin.

V. CONCLUSITON

In this paper, the bearing electric damage in the form of ‘washboard’ corrugated groove of wind turbine bearings usually evolves gradually with operating period and localised in load zone. This means that the vibration responses are similar to that of normal fatigue detects but can have different resonances due to the difference in surface formalisations.

Through the simulation signal analysis, the spectrum exhibit certain features of modulation but it is difficult to identify the modulating frequency, and the conventional envelope spectrum also fails in separating the fault signal. However, MSB can indicate clearly the modulation effect between the fault frequency at 70Hz including its harmonics and the resonance at 1000Hz. This shows that the MSB method can be applied to extract a clean or sparse bispectrum by combining the modulating components and carrier components along with the high performance of noise suppression.

From the signals obtained from the experiments, the amplitude of the signal increase as the damage becomes serious when the bearing damaged part on the raceway caused by the electric damage bearing evolved gradually into ‘washboard’ corrugated groove from the pits. From the time domain waveform and envelope spectrum, amplitude increase and fault characteristic frequency are obtained. However, the reason why the faults occur cannot be determined owing to the similar feature features. On the other hand, MSB analysis, which supresses the noise and integrates the modulating components and carrier components to obtain a clean or sparse results shows not only the significant peaks at fault frequency, but also significant differences in carrier frequencies for different fault cases. MSB analysis can denote the occurrence of local defects and the fault types, therefore MSB is a reliable and accurate detector to monitor the conditions of bearings.

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