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Comparison between shock pulse method and vibration analysis methods on early fault detection of rolling element bearing

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In this paper, the vibration analysis methods and shock pulse method (SPM) are compared in order to detect the unhealthy condition as well as fault type in the early stages of rolling element bearing (REB) degradation. To analyze vibration signals, three weak signature detection methods based on continuous wavelet transform (CWT), empirical mode decomposition (EMD) and envelope technique are employed. A set of accelerated life tests on REBs was designed and performed in CM lab of Sharif university of technology. Seven tests were conducted and vibration signals, as well as shock pulse signals, were recorded regularly. The trend of vibration level and shock pulse level are compared for early detection of the unhealthy condition in REBs. In addition, the extracted spectrums from SPM, CWT, EMD, and envelope techniques are studied to detect bearing characteristics frequencies (BCFs) to diagnostics. Results show that SPM has better performance on early fault detection of REBs rather than vibration analysis techniques.

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1. Introduction

Rolling element bearings (REBs) are one of the most critical components in rotating machines. Failure of these components may lead to fatal and costly breakdowns in rotating industrial machinery. Therefore, it is significant to detect faults at early stage accurately. Vibration signals recorded from the bearing housing contains information about the health condition of REBs [1]. However, raw signals often include various noises. To monitor the health condition of REBs, it is necessary to extract the detailed hidden information behind these noises [2]. When faults in REBs are in early stage, vibration in bearing characteristic frequencies (BCFs) are usually much weaker than the noise. So, it is difficult to detect REBs faults in the early stage. Signal processing methods are employed to extract more evident information corresponded to the incipient faults of REBs. The vibration analysis methods and shock pulse method (SPM) are two popular condition monitoring (CM) methods for detecting defects of REBs. SPM measures and analyzes the elastic waves propagated due to initial cracks opening and closing which leads to detect these cracks in a very early stage of degradation. Some researches have compared the capabilities of these two methods in REBs fault detection [3-5]. A comparison between vibration analysis and SPM presented by Tandon et al. [3]. For defects on the outer race, they investigated the effect of fault location corresponding to the load zone on the recorded vibration and SPM data. Additionally, comparing signals of the healthy and unhealthy REBs, they deduced that shock pulse level is more sensitive to react due to load and speed variation in defective REBs rather than vibration level. Another comparison between vibration analysis, current analysis, acoustic emission (AE) and SPM was presented by Tandon et al. [4], for detecting REB defects (a seeded defect in the outer race) in induction motors. They showed that the AE method and SPM have better performance in fault detection. In another research, Yang et al. [5] studied the vibration analysis technique and SPM in an actual industrial case-study. They compared SPM and vibration signals in the frequency domain and finally reported better prediction of SPM rather than vibration analysis. Behzad et al.[6, 7] investigated SPM and vibration envelope technique for early fault detection as well as prognosis of the REBs. They showed the better performance of SPM for both aims.

Since vibration record and analysis is a very popular CM technique in industry, early fault detection from the analysis of vibration signals is very useful and significant. Some signal processing approaches like continuous wavelet transform (CWT) and empirical mode decomposition (EMD) have been developed to detect weak signatures in vibration signals that can be used for early fault detection of rotating machines. It is shown in the literature that these advanced approaches can usually detect the fault signatures earlier than popular frequency domain analysis like spectrum analysis and envelope technique [8]. However, all previously mentioned references [3-7] have only compared SPM with the results of the analysis on spectrums extracted from fast Fourier transform (FFT) of time waves or envelope signals. This study is planned to compare SPM results for REBs early fault detection with two advanced signal processing methods on vibration signals, including CWT and EMD.

CWT has been employed widely in the last decades for signal processing and diagnosis of REBs. Using CWT, many researchers have developed and optimized filtering procedures in order to extract better features [6, 9-14]. Various wavelets have been developed for filtering signals, eg. Morlet, Haar, Daubechies, Coiflet, etc [15]. Morlet wavelet has been used in demodulation and de-noising the signals recorded from REBs, successfully. Since the shape of Morlet wavelet is similar to impulse-like waves generated by defective REBs. Qiu et al. [16] used minimum Shannon entropy to optimize the wavelet shape factor and singular value decomposition (SVD) method to choose the appropriate scale for the wavelet transform (WT). Su et al. [17] developed a new hybrid method based on optimal Morlet wavelet filter and autocorrelation enhancement. To eliminate the frequencies associated with interferential vibrations, they filtered the vibration signals with a band-pass filter. Parameters of this wavelet-based filter have been optimized by a genetic algorithm. In addition, they proposed an algorithm for removing the residual in-band noise of filtered signals to the enhancement of signal-to-noise quality. Jiang et al. [18] presented a de-noising method based on adaptive Morlet wavelet and SVD. They applied this method in order to feature extraction from vibration signals recorded from the wind turbine gearbox. They used modified Shannon entropy to optimize center frequency and bandwidth parameters. Then, they employed an improved matrix construction method to construct the matrix of the wavelet coefficient, and obtain scale periodical exponential (SPE) spectrum by SVD for selecting the appropriate transform scale. Morsy et al.[19] presented a method based on optimal Morlet wavelet filter and envelope detection. They optimized the wavelet filter to maximize the kurtosis value. Qin et al. [20] proposed a new approach using the optimized Morlet WT, kurtosis index, and soft-thresholding to extract proper features for detecting weak transient signatures.

EMD is another powerful signal processing technique that has been extensively studied and widely applied in fault diagnosis of rotating machinery[21-31]. This method has attracted attentions
due to its capability to the self-adaptive decomposition of non-stationary signals. Some researchers have applied EMD based methods on REBs fault detection [21-26, 28, 29]. Junsheng et al. [21] proposed the energy operator demodulation approach based on EMD for bearing fault detection. To this aim, they used EMD method to decompose a signal into the number of intrinsic mode functions (IMFs). Then, they applied the energy operator demodulation method to each IMF for detecting weak signatures. Fan and Zuo [22] employed the amplitude acceleration energy of IMFs to represent fault characteristics of bearings and gears. In their study, the amplitude acceleration energy of the IMFs was proposed as an indicator of the impulsive features that are often associated with mechanical component faults. Tsao et al. [24] proposed a method based on EMD to select the resonant frequency band. They employed overlap frequencies of IMFs spectrums for choosing frequency band-pass of the traditional envelope analysis method. Ben Ali et al. [29] used EMD and artificial neural network (ANN) for automatic fault diagnosis of REBs. They proposed a mathematical procedure for selecting the most significant IMFs. Then they employed an ANN to classify bearings defects. Dybala et al. [28] used EMD for dividing a vibration signal into three parts including noise-only part, signal-only part, and trend-only part. Then, they used spectral analysis of the empirically determined local amplitude on the noise-only part for early fault detection of REBs.

In this paper, vibration analysis methods (including CWT and EMD) and SPM are applied to the data recorded in a set of accelerated life tests on REBs in order to compare their capability on early detection of the unhealthy condition as well as the defect type. To this aim, seven accelerated life tests have been planned and conducted. Vibration data and shock pulse data have been measured regularly during the whole life of seven REBs. Results show that, generally, SPM has detected the unhealthy condition and the fault type earlier than vibration analysis methods.

The outline of this paper is arranged as follows: In section 2, the concepts of SPM, CWT, and EMD are reviewed. Next, experimental setup and accelerated life tests on REBs are explained in section 3. In section 4, SPM and vibration analysis techniques (CWT, EMD, and envelope analysis) are applied to the experimental data in order to compare their capability on early detection of REBs unhealthy condition and the defect type. Finally, the conclusion is presented in section 5.

2. Materials and methods

In this section, the physical bases and procedures of three approaches, which are going to be studied for early fault detection of REBs, will be introduced and discussed. Next, these approaches will be applied to actual vibration signals and compared together in the next section.

2-1. SPM

SPM was patented in 1969 and SPM Instrument AB was established in 1970 to develop this technology for CM of industrial machines [3]. For four decades, the original SPM has been used for the fast, easy, and reliable diagnosis of REBs successfully [32] SPM considers the REBs as a shock generator rather than a vibration generator. Shock pulses are elastic waves that are propagated in a solid medium. These shock pulses may be generated by surface contacts during crack opening and closing. Therefore, measuring the shock pulses trend may be because of crack existence and propagation in the medium. The Shock pulse transducer which is developed by SPM Instrument, is a piezoelectric based sensor which amplifies the signal in the range of 32 kHz. This region is corresponded to the natural frequency range of the sensor. The measured signal is filtered in a specific range around this frequency. Basically, the main structure of this transducer is similar to the piezoelectric accelerometers. However, they measure the signal in a limited frequency bandwidth [33]. The measurable frequency range of popular accelerometer are usually less than 20 kHz. That is because of the limitation in the linear range of their frequency response. However, the SPM Instrument shock pulse transducer is designed to measure high-frequency signals. Since the elastic waves in solids has high frequency, the popular accelerometers cannot be used for recording them while the mentioned shock pulse sensor claims to record such signals.

In REBs, surface and subsurface cracks in contacting elements are in the cyclic opening and closing condition and propagate because of rolling contact fatigue (RCF). So, it is expected that SPM can detect crack initiation and propagation in the very early stage. Transmission from one medium to another one is influencing the characteristics of shocks. Two popular features introduced by the SPM group are known as HDm and HDc [32] HDm, which is the highest shock pulse found during the measurement period, is a piece of evidence for crack existence. While HDc is an indicator that represents the lubrication condition in REB. In this paper, the trend of HDm is employed to track the degradation in elements of REB. In addition, the envelope filtered time wave is analyzed in the frequency domain to detect defect mode. This spectrum is provided automatically in SPM software.

2-2. CWT method

The CWT of a finite energy signal x(t) with an analyzing mother wavelet $\psi(t)$ is defined as the convolution of x(t) with a scaled and conjugated wavelet [17]:

$$W_b(a) = |a|^{-1/2} \int_{-\infty}^{\infty} x(t)\psi^*(\frac{t-b}{a})\, dt \tag{1}$$

where a is the scale factor and b is time location, the term $|a|^{-1/2}$ is used to ensure energy preservation. There are many types of wavelet functions available to use for different purposes. For fault detection in REBs, Morlet wavelet filter is adopted in demodulation and de-noising since the shape of Morlet wavelet is very similar to the impulse-like feature of defective REB signals. The Morlet wavelet has been applied to extract the fault feature and achieve relatively satisfying results in REBs diagnostic [8]. In this research, Morlet wavelet is employed to analyze signals recorded from REBs. Morlet wavelet formula is described as follows [17]:

$$\psi(t) = ce^{-\sigma^2 t^2}\, e^{j2\pi f_0 t} \tag{2}$$

and Fourier transform of Morlet wavelet is extracted as [17]:

$$\psi(f) = ce^{-(\pi^2/\sigma^2)(f-f_0)^2} \tag{3}$$

The wavelet has the shape of a Gaussian window in the frequency domain, where f_0 is the center frequency of the window and σ is the shape factor that determines its bandwidth. Selecting optimal f_0 and σ is an important step to obtain a proper filtering bandwidth. To this aim, Su et. al. [17] proposed an approach based on genetic algorithm optimization to find the best values for f_0 and σ which minimizes Shannon entropy rule. This leads to finding the optimum Morlet wavelet filter. The mentioned method, which is previously proposed in [17], will be used for extracting defect signatures from the vibration signals of faulty REB in the early stage of fault propagation in this paper to compare with SPM analysis.

2-3. EMD method

EMD algorithm which was firstly introduced by Huang et al. [33] decomposes a vibration signal into some IMFs. An IMF is a function that satisfies the following two conditions: (1) In the whole time domain, the number of extrema and the number of zero-crossings must either equal or differ at most by one, and (2) At any point, the mean value of the envelope defined by local maxima and the envelope defined by the local minima is zero. EMD provides a decomposition rule to extract the oscillation modes of a given signal through a sifting process [28] To improve the performance of the EMD algorithm for fault detection, Fan and Zuo [22] proposed to calculate the Fourier transform of IMFs' acceleration energy for seeking fault signatures. They concluded that this modification leads to better results. This method will be also employed for extracting defect signatures from the vibration signals of faulty REB in the early stage of fault propagation in this paper to compare with SPM analysis.

3. Experimental setup

To comparison SPM and three advanced signal processing techniques on vibration condition monitoring (VCM) records, a set of accelerated life tests on REBs was designed and performed in CM lab of Sharif university of technology. In the accelerated life test, an excessive radial load (comparing the usual loads that applies to the REB in normal service) applies to REBs in order to have the degradation in a short period of time. The faults initiate and grow naturally in the accelerated life tests. The test rig is shown in Fig. 1. This test rig hosts a test REB at one end of the shaft. Two larger REBs also support the shaft. The shaft is coupled to an AC electromotor as the drive of the system through pulley and belt mechanism. The test REB is 6907 deep groove single-row bearing. The main dimensions and corresponding BCFs of test REB are presented in table 1. The loading system pulls the housing of test REB downward. Therefore, the loading zone is located at the top of the test REB. Experiments were performed in constant operating conditions including 2000 rpm rotational speed and 9000 N radial load. Both shock pulse and vibration of test REB were recorded during the test through a shock pulse sensor (Model: SPM44000) and an accelerometer (Model: SLD144B-M8), respectively. Both sensors were installed on the top of REB housing (above loading zone of test REB) as shown in Fig. 1. Shock pulse signal and vibration data have been collected every 1 minute. The sampling frequency of SPM and vibration signals were 102 kHz and 25.6 kHz, respectively. Each record of vibration and shock pulse includes 32768 and 16386 samples, respectively. The failure threshold was defined on the amplitude of the acceleration signal. So that, touching the amplitude of 30g was the final failure criterion and accelerated life tests were stopped at this point.

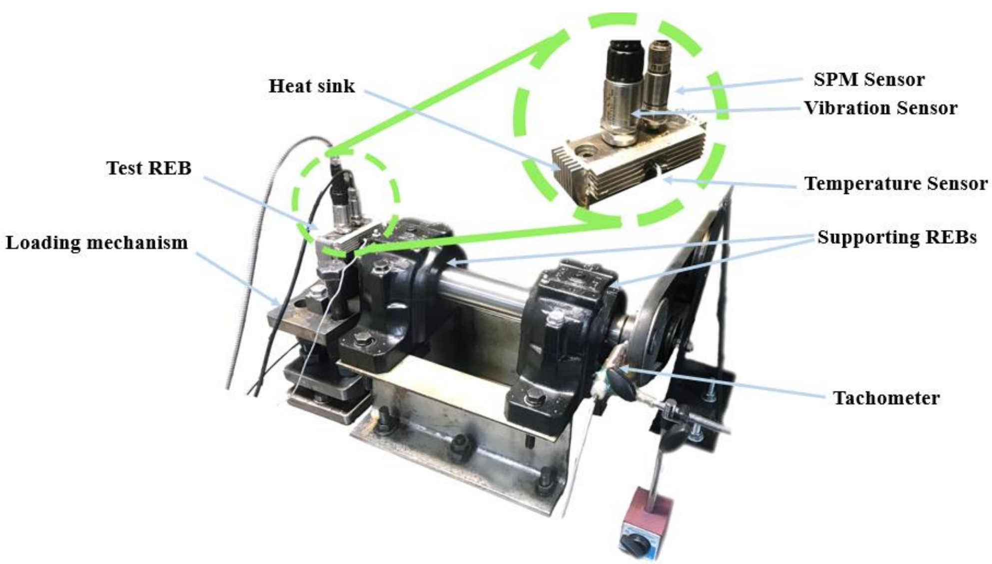

Fig. (1) Accelerated life tests on REBs experiments test rig

Seven run-to-failure experiments performed in the described test-rig and corresponding vibration and shock pulse data were recorded. At the end of each experiment, the test REB was disassembled and final failures were recognized through visual inspection (Fig. 2). Table 2. Represents the life of each test REB and corresponding verified failure mode at the end of the experiment

Table 1. Characteristics of test REB

Dimensions	OD	Outer Diameter (mm)	55
	ID	Inner Diameter (mm)	35
	W	Width (mm)	10
	N	Ball numbers	11
BCFs	BPFO	Ball Pass frequency outer race	204.5
	BPFI	Ball Pass frequency inner race	262.14
	BSF	Ball spin frequency	132.9
	FTF	Fundamental cage frequency	14.6
Dynamic Characteristics	C_0	Static load rating (N)	6850
	C	Dynamic load rating (N)	9550

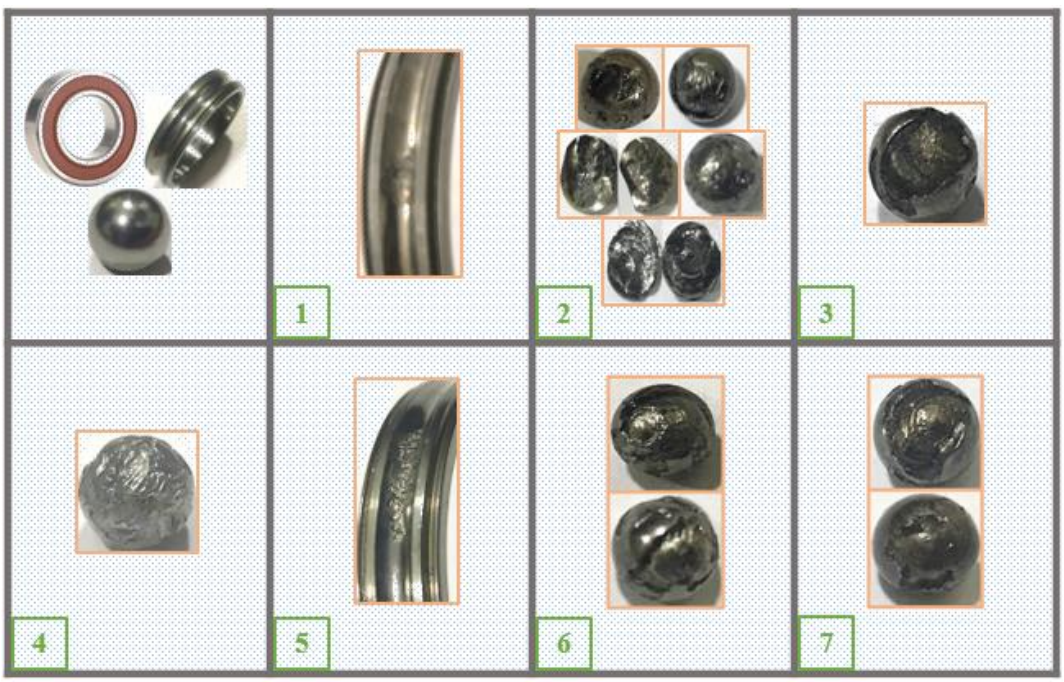

Fig. (2) Visual inspection results of failures in the elements of accelerated life test REBs

Table 2. Summary of conducted accelerated life tests

Test No.	The useful life of the test REB (second)	Verified failure mode at the end of the experiment
1	11670	Inner race
2	10051	Rolling element
3	30205	Rolling element
4	306610	Rolling element
5	26294	Inner race
6	13704	Rolling element
7	14742	Rolling element

4. Experimental results analysis

In this section, the vibration analysis and SPM will be compared for two objectives: detecting health condition and detecting fault type, both in the early stages of REB degradation.

4-1. Comparison between SPM and vibration analysis for detecting early-stage degradation

The trend of root mean square (RMS) extracted from the vibration acceleration signals (Vib_{rms}), and the trend of HDm, extracted from the shock pulse signals ($\mathrm{SPM}_{\mathrm{HDm}}$) for all seven accelerated life tests of REBs, which described in section 3, are plotted in Fig. 3. In this figure, both mentioned trends of each accelerated life test have been depicted in one plot. So, the moment that both trends begin to increase, can be observed and compared together, obviously. Ten percent growth of these trends is interpreted as the degradation of REB. The physical explanations behind Vib_{rms} growth and $\mathrm{SPM}_{\mathrm{HDm}}$ growth are different. Therefore, it is not generally expected to observe the growth initiation of both features simultaneously. To study the purpose of this section, the moment of growth initiation of both trends are compared. To this aim, the life of each REB is divided into three regions. The first region (that is shown with green color and square markers) corresponds to the healthy condition of REB. Since, both features, Vib_{rms} and $\mathrm{SPM}_{\mathrm{HDm}}$ have a steady trend. In the second region (that is shown with pink color and triangle markers) one of the trends has started to grow while the other trend has still a steady value. The third region (that is shown with red color and circle markers) corresponds to observing growth in the trend of both features. Investigating trends of all seven accelerated life test results depicted in Fig. 3 show that $\mathrm{SPM}_{\mathrm{HDm}}$ has started to grow earlier that Vib_{rms} in four tests, while in the other three tests, both features have begun to grow simultaneously. Comparing these observations with the reported results in table 2 show that the failure corresponded to rolling element defect, in four tests which $\mathrm{SPM}_{\mathrm{HDm}}$ was reacted earlier. However, in the two of the three other tests, the failure corresponds to the inner race. And, in one other test, it corresponds to the rolling element. As a conclusion, the results show that $\mathrm{SPM}_{\mathrm{HDm}}$ has usually a better performance in detecting the early-stage unhealthy condition of tested REBs rather than Vib_{rms}.

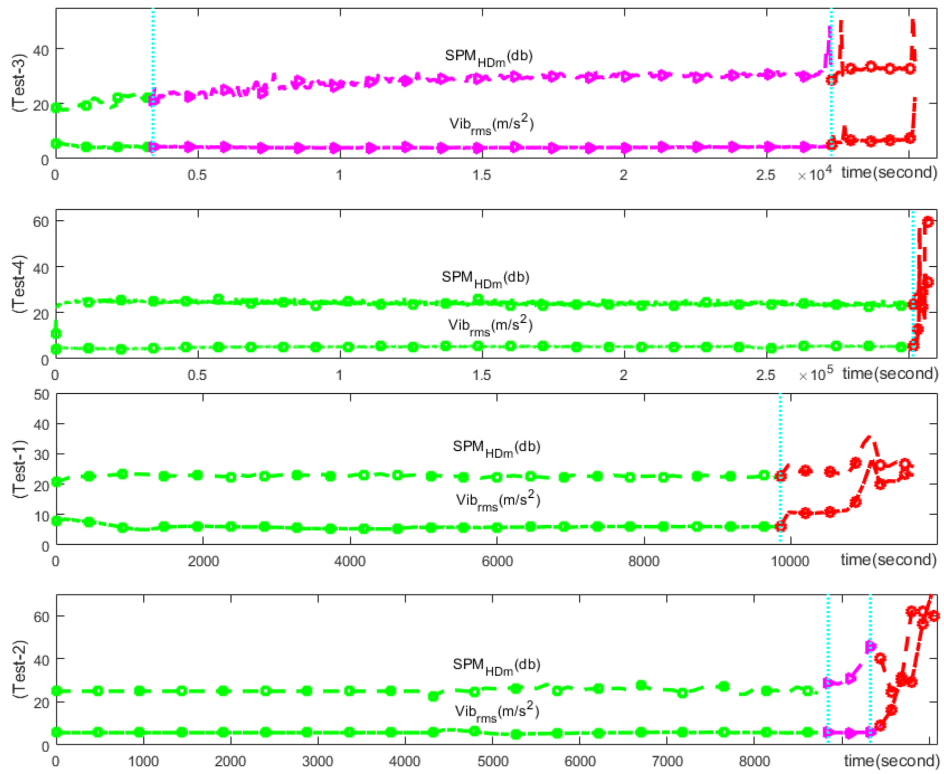

Fig. (3-1) The trend of Vib$_{rms}$ and SPM$_{\mathrm{HDm}}$ for seven REBs accelerated life tests

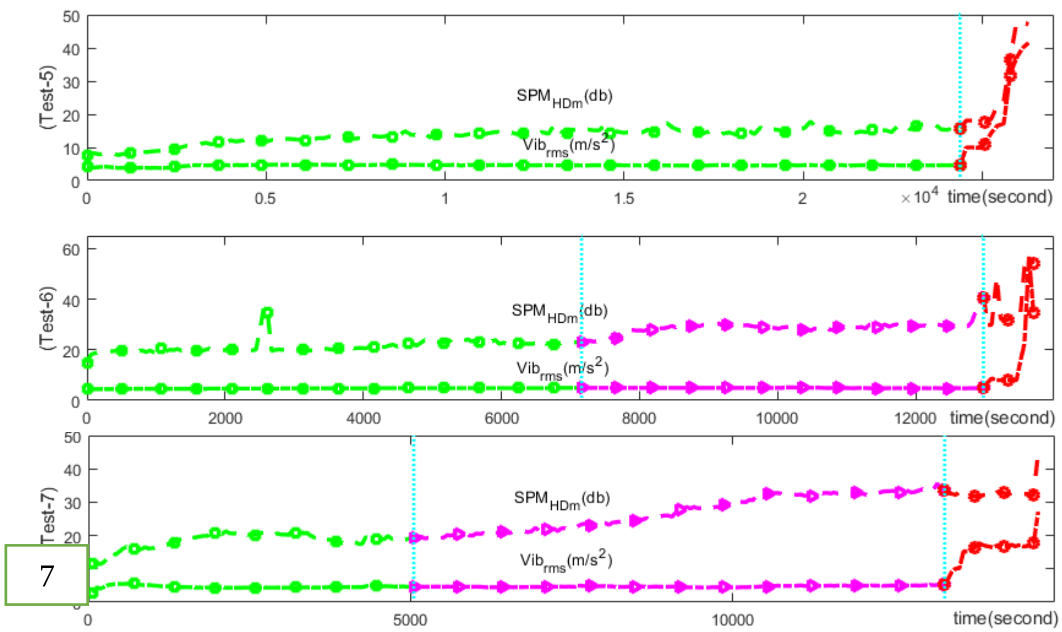

Fig. (3-2) The trend of Vib$_{rms}$ and SPM$_{\mathrm{HDm}}$ for seven REBs accelerated life tests

4-2. Comparison between SPM and vibration analysis for detecting early-stage fault type

In the previous section, the trend of Vib_{rms} and SPM_{HDm}were studied and compared. It was shown that SPM_{HDm} has better performance for early detection of defect occurrence, rather than Vib_{rms}. In this section, detecting of defect type in the early degradation stage is investigated. To detect the type of initiating fault, seeking for BCFs in vibration signals and SPM signals is performed. SPM analyzing software provides the signatures after post-processing the acquired data at each measuring point. On the other hand, to analyze vibration signals, two weak signature analysis methods based on CWT and EMD are employed. The envelope analysis technique is also applied to vibration signals as a very popular industrial method for fault detection of REBs in the early-stage of degradation. The resonant area is selected for band-pass filter in envelope analysis. In these tests, the frequency band [2000,3000] Hz is employed. More details on analyzing methods that are used in this section were previously described in section 2. To study and compare the performance of vibration analysis and SPM for early detection of defect types, the trends of features have swept with four mentioned techniques. The time corresponded to the first signal in which any of the four techniques could reveal the BCFs have extracted and reported in table 3 for all seven run to failure tests of REBs which described in section 3. Here, the results of the analysis on only one accelerated life test is presented because of space limitation. To this aim, Fig. 4-8 depicts the results of the analysis on accelerated life test No. 2. Fig. 4 presents the trend of Vib_{rms} and SPM_{HDm} of REB #2 in the last third of its useful life. Four points in these two trends are marked as I, II, III, and IV. These points correspond to the initial detection of BCF with four techniques which are listed in table 3. Point I corresponds to the moment that SPM has detected the rolling element characteristic frequency, its harmonic, and sidebands clearly for the first time. However, none of the early detection analysis on the vibration signal could extract noticeable results at this moment. The results of the analysis on the time signals of SPM and vibration at this moment are depicted in Fig. 5. Similarly, points II and III correspond to the moments that CWT and EMD have detected the BCFs of rolling elements for the first time, respectively. Fig. 6 and 7 present the results of the analysis at moments II and III, respectively. As shown in these figures, SPM and CWT could extract the BCFs corresponded to rolling elements clearly in Fig. 6. And, in Fig. 7, besides the two mentioned techniques, the EMD technique could also detect the same BCFs. However, point IV is the first point in which the envelope technique could detect the signatures later than other techniques. Fig. 8 shows the results of the analysis with four methods at the moment IV.

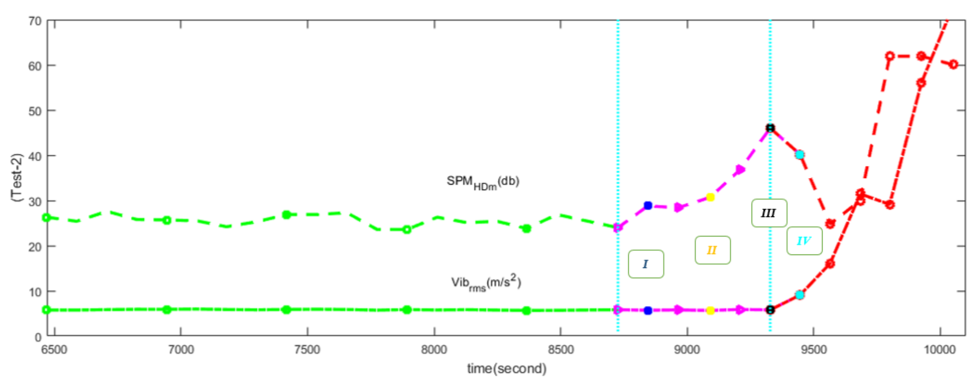

Fig. (4) Trend of SPM_{HDm} and Vib_{rms} accelerated life test No.2 (*I*: the earliest fault type detection moment by SPM, *II*: the earliest fault type detection moment by CWT, *III*: the earliest fault type detection moment by EMD, *IV*: the earliest fault type detection moment by envelope technique)

Similar analysis as explained above for REB#2 have been performed for other REBs, and only the final results have reported briefly in table 3. The presented results in this table show that SPM could always detect the defect type earlier or simultaneously with vibration analysis techniques. In the accelerated life tests of REBs #1, #4, and #5, which the growth on the trend of Vib_{rms} and SPM_{HDm} were initiated at the same time, four employed techniques have detected the defect type at the almost same time. While, in the other accelerated life tests, SPM could detect BCFs earlier than the vibration analysis techniques. Meanwhile, comparing two studied early detection methods for vibration signals on conducted REBs accelerated life tests shows that CWT has presented relativity some earlier reaction to defects rather than EMD technique.

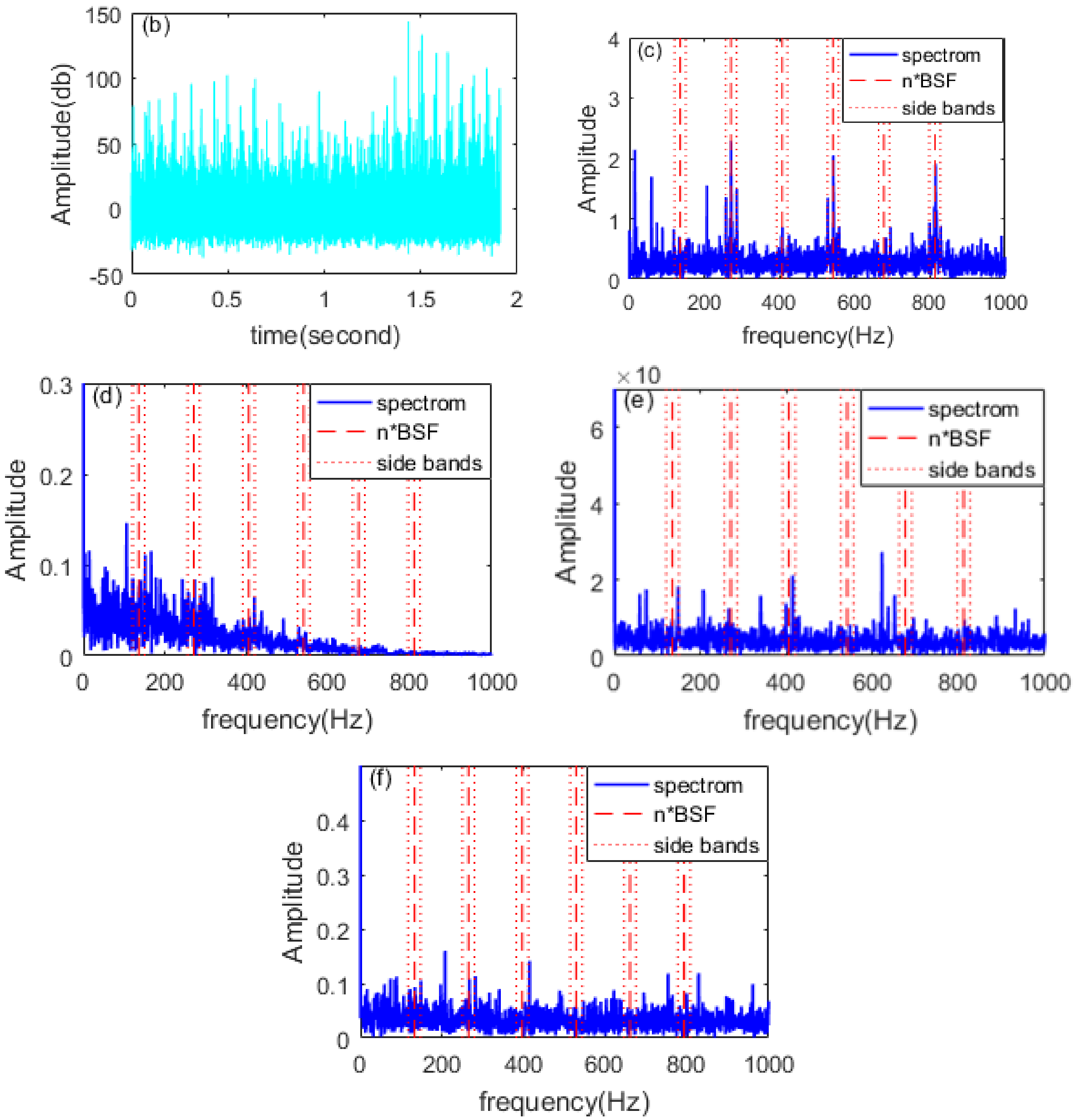

Fig. (5) Applying SPM and all vibration techniques on signals recorded at t = 8844 second (point *I* in Fig. 4) on accelerated life test No.2, (a) vibration time signal, (b) shock pulse time wave, (c) spectrum of shock pulse level, (d) spectrum of the Morlet wavelet filter, (e) spectrum of filtered signal by EMD, (f) spectrum of vibration envelope.

Table 3. Compression between vibration analysis technique and SPM for early fault type detection

Test number	The useful life of the test REB (second)	Moment of inanition of each region (second)		Moment of the first time BCF detection by each technique (second)			
		Second region	Third region	SPM	CWT	EMD	Envelope
1	11670	9856	9856	9856	9856	9856	9856
2	10051	8726	9445	8844	9090	9327	9445
3	30205	3427	27268	3484	27268	27268	27325
4	306610	301412	301412	301526	301526	301526	301526
5	26294	24379	24379	24553	24553	24553	24553
6	13704	7161	12984	12011	12984	12984	13098
7	14742	5051	13290	9057	13290	13290	14742

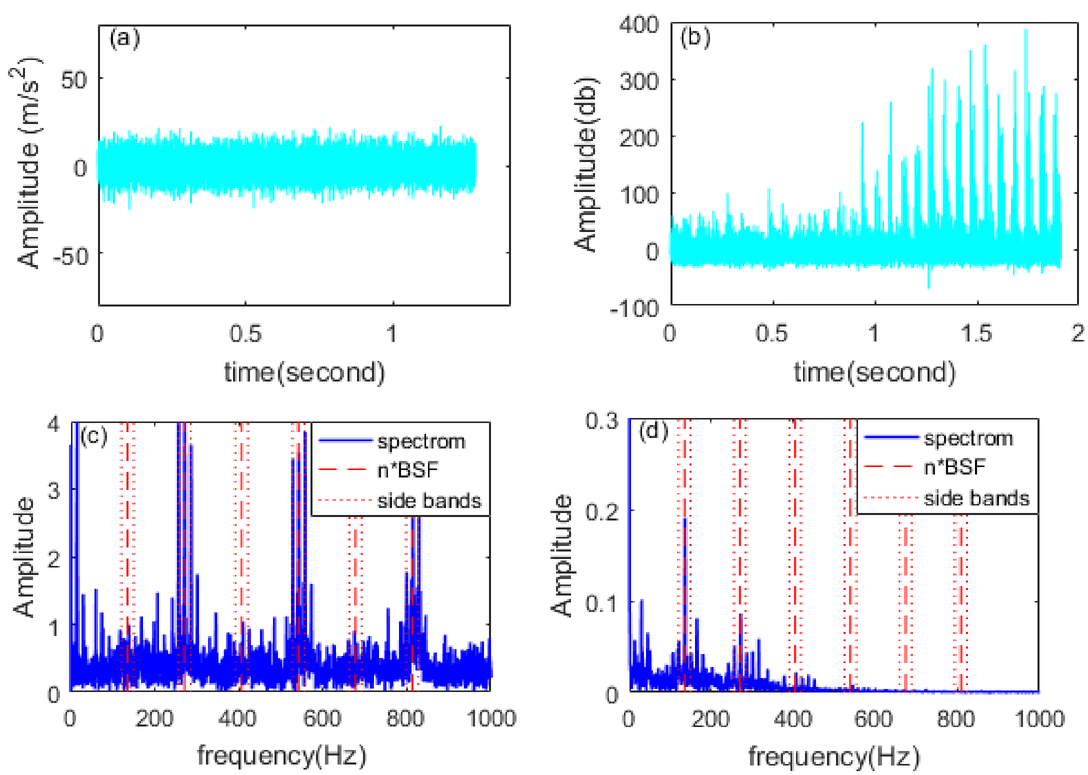

Fig. (6) Applying SPM and all vibration techniques on signals recorded at t = 9090 second (point *II* in Fig. 4) on accelerated life test No. 2, (a) vibration time signal, (b) shock pulse time wave, (c) spectrum of shock pulse level, (d) spectrum of the Morlet wavelet filter, (e) spectrum of filtered signal by EMD, (f) spectrum of vibration envelope.

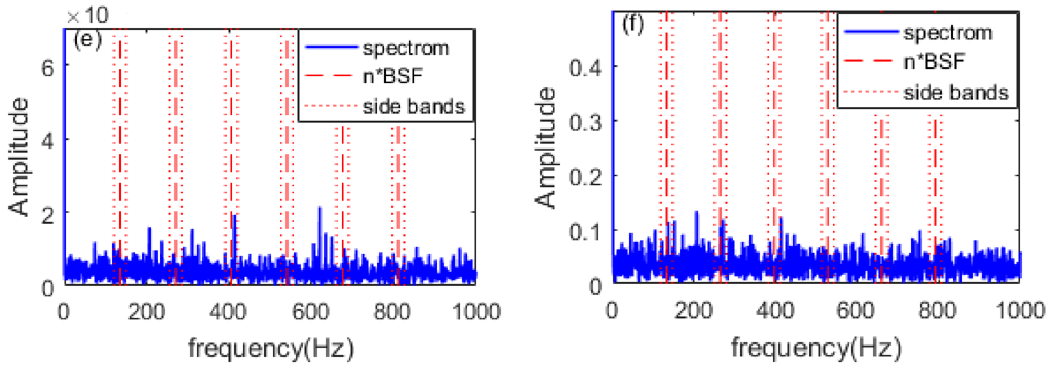

Fig. (6) Applying SPM and all vibration techniques on signals recorded at t = 9090 second (point *II* in Fig. 4) on accelerated life test No. 2, (a) vibration time signal, (b) shock pulse time wave, (c) spectrum of shock pulse level, (d) spectrum of the Morlet wavelet filter, (e) spectrum of filtered signal by EMD, (f) spectrum of vibration envelope.

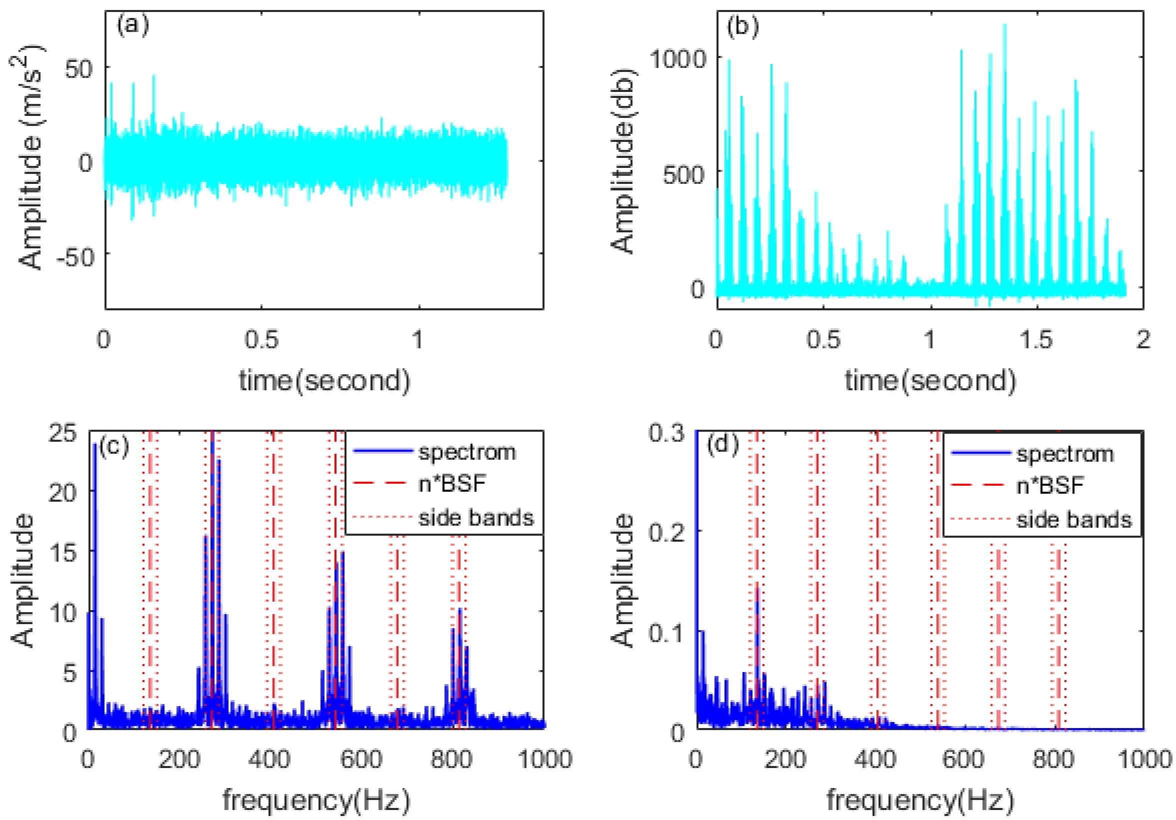

Fig. (7) Applying SPM and all vibration techniques on signals recorded at t = 9327 second (point III in Fig. 4) on accelerated life test No. 2, (a) vibration time signal, (b) shock pulse time wave, (c) spectrum of shock pulse level, (d) spectrum of the Morlet wavelet filter, (e) spectrum of filtered signal by EMD, (f) spectrum of vibration envelope.

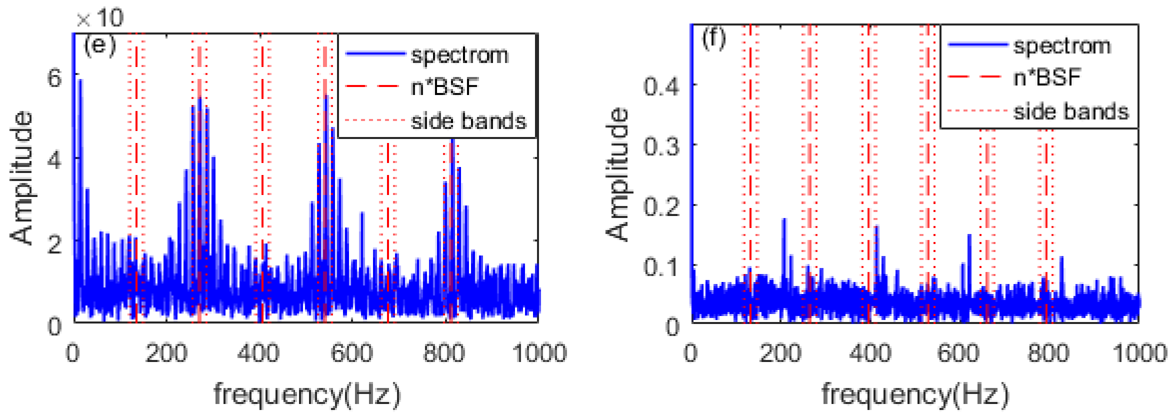

Fig. (7) Applying SPM and all vibration techniques on signals recorded at t = 9327 second (point *III* in Fig. 4) on accelerated life test No. 2, (a) vibration time signal, (b) shock pulse time wave, (c) spectrum of shock pulse level, (d) spectrum of the Morlet wavelet filter, (e) spectrum of filtered signal by EMD, (f) spectrum of vibration envelope.

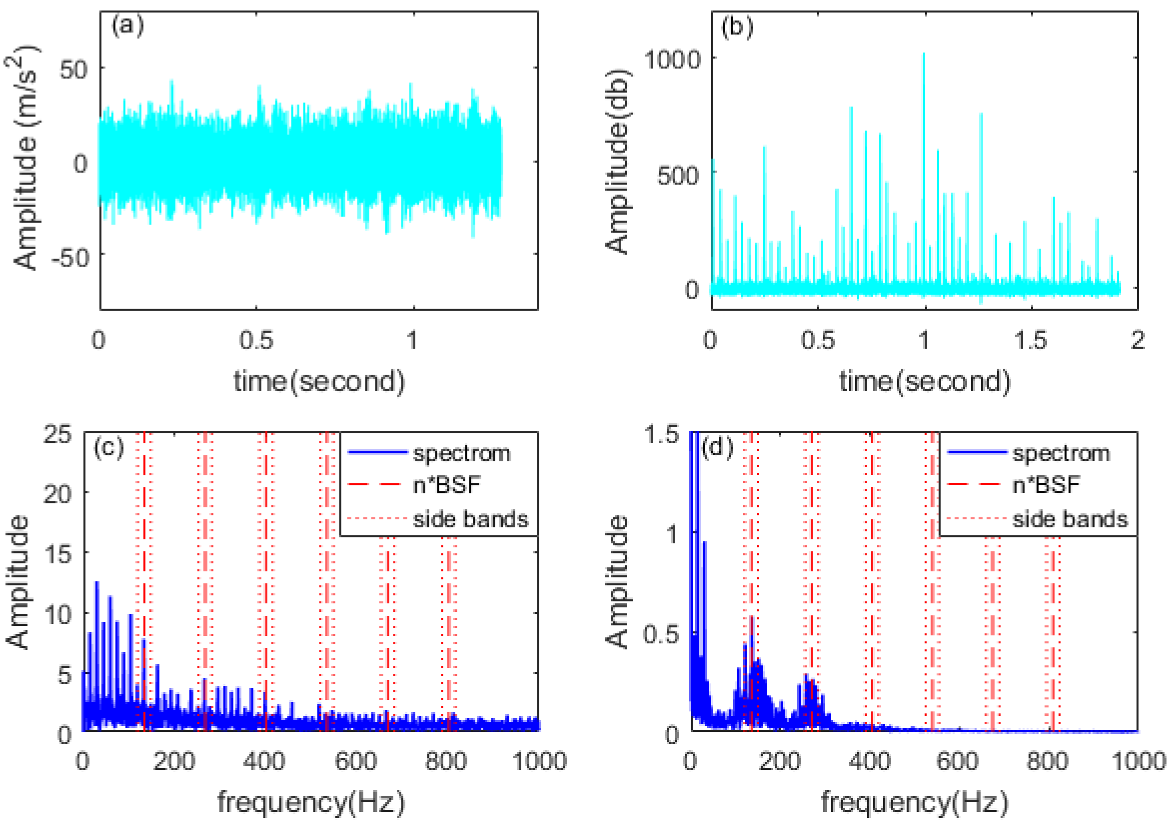

Fig. (8) Applying SPM and all vibration techniques on signals recorded at t = 9445 second (point IV in Fig. 4) on accelerated life test No. 2, (a) vibration time signal, (b) shock pulse time wave, (c) spectrum of shock pulse level, (d) spectrum of the Morlet wavelet filter, (e) spectrum of filtered signal by EMD, (f) spectrum of vibration envelope.

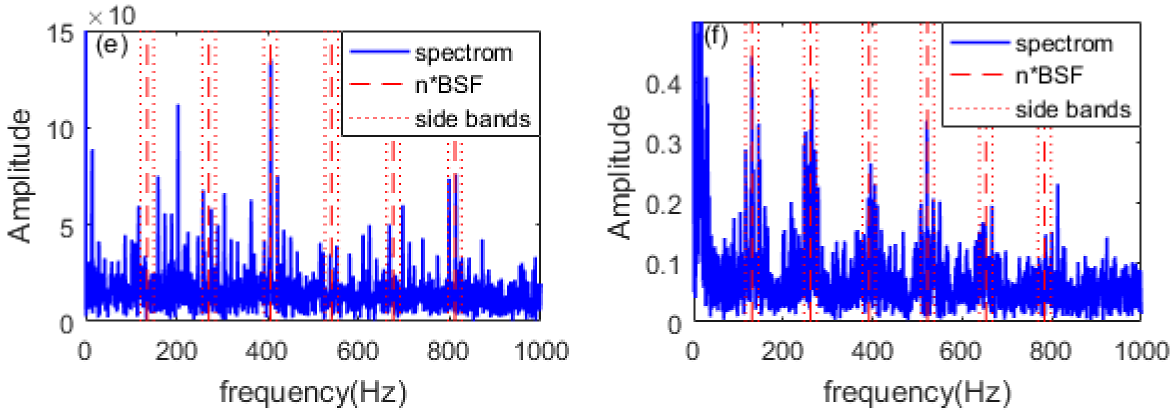

Fig. (8) Applying SPM and all vibration techniques on signals recorded at t = 9445 second (point *IV* in Fig. 4) on accelerated life test No. 2, (a) vibration time signal, (b) shock pulse time wave, (c) spectrum of shock pulse level, (d) spectrum of the Morlet wavelet filter, (e) spectrum of filtered signal by EMD, (f) spectrum of vibration envelope.

4-3. Discussions on the results

According to the presented result in subsections 4.1 and 4.2, SPM provides better performance in detecting the unhealthy condition and defect type in the early-stages of REBs degradation rather than vibration analysis techniques. To explain the reason for the better performance of SPM in the earlier detection of rolling element defects, it should be noticed to the physical descriptions behind it. Shock pulse sensors are installed in the housing of REB and close to the outer race to detect the generated elastic waves resultant from breathing cracks. For the propagating cracks in the inner race, elastic waves must pass through four contacting surfaces (the contact surfaces between the inner race and rolling element, rolling element and outer race, outer race and housing, and housing and sensor probe) to reach the SPM sensor probe. Elastic waves (especially high-frequency waves like shock pulse) are weakened during passing through the contacting surfaces. Meanwhile, the oil film which usually exists between REB elements can damp the elastic waves. On the other hand, if the breathing cracks are in the surface or subsurface of rolling elements, their generated elastic waves pass less contacting surfaces to reach the sensor probe. Therefore, better performance of SPM on detecting rolling element defects seems reasonable. Consequently, it is expected that SPM has the best performance in detecting defect initiation and growth in the outer race. However, this type of defect did not occur in the conducted accelerated life tests.

Two important behavior on the trend of SPM_{HDm} makes it a good candidate feature for remaining useful life (RUL) estimation. firstly, this feature has a considerable earlier reaction to fault initiation rather than vibration-based trends (e.g. accelerated life tests 3, 6, and 7). Secondly, this trend has relatively monotonic behavior and a meaningful threshold for detecting the failure. These two aspects are considered for using this feature in data-driven models for the RUL estimation of REBs, which will be the purpose of our future study.

5. Conclusion

In this paper, the vibration analysis (three methods based on CWT, EMD and envelope analysis) and SPM were compared to detect the fault in the early stage of REBs degradation. The employed methods applied to the data of conducted accelerated life tests on REBs. Comparing the trend of Vib_{rms} and $\mathrm{SPM}_{\mathrm{HDm}}$ showed that SPM relatively reacts to the fault initiation earlier in some experiments. Whereas, in some other experiments, both trends began to increase simultaneously. In order to detect fault type, three vibration analysis methods applied to the vibration signals to extract the fault signatures. In the experiments that the trend of $\mathrm{SPM}_{\mathrm{HDm}}$ was reacted earlier than Vib_{rms}, the spectrum of shock pulse signals could reveal the BCFs earlier than other techniques. Among the three employed techniques for vibration signal analysis, CWT based technique was the first one for detecting weak signatures after SPM. Next, EMD could detect the BCFs. However, the envelope technique was the last one for detecting signatures, usually after Vib_{rms} increase observation.

In all the experiments which the trend of $\mathrm{SPM}_{\mathrm{HDm}}$ has earlier growth rather than Vib_{rms} trend, the fault was on the rolling elements. However, in two experiments, which inner race was defected, both trends have started to increase simultaneously. It was concluded that the reason for earlier detection of SPM rather than vibration analysis methods, may depend on defect type and the distance between defect location and sensor location.

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