Using appropriate IMFs for envelope analysis in multiple fault diagnosis of ball bearings

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\begin{abstract}
The traditional envelope analysis is an effective method for the fault detection of rolling bearings. However, all the resonant frequency bands must be examined during the bearing-fault detection process. To ameliorate the above deficiency, this paper presents a new concept based on the empirical mode decomposition (EMD) to choose an appropriate intrinsic mode function (IMF) for the subsequent envelope analysis. By virtue of the band-pass filtering nature of EMD, the resonant frequency bands of structure to be measured are captured in the IMFs. As impulses arising from rolling elements striking bearing faults modulate with structure resonance, appropriate IMFs are potentially able to characterize fault signatures, instead of always using IMF 1. In the study, dual- and triple-fault bearings are used to justify the proposed method and comparisons with the traditional envelope analysis are made.

\end{abstract}

1. Introduction

Rolling bearings are important mechanical elements of rotary machinery, such as cutting machines, motors, electrical generators and turbo-pumps etc. Bearing faults are a common cause of machine breakdown. For reducing machinery downtime, the detection of rolling-bearing faults is crucial. Fault detection techniques of roller bearings, such as vibration, acoustic, and temperature measurements, have been investigated for decades. Among these, vibration measurement and analysis are extensively employed; more specifically, vibration signals measured from bearing faults exhibit an amplitude modulation phenomenon that combines the feature frequencies of the bearing defects with the structural resonance of machines. Therefore, many diagnosis approaches are devoted to the research of the modulation resonance analysis. Especially, for the envelope analysis technique it was presented in the early 1970s by Mechanical Technology Inc\textsuperscript{[1]} and originally called the high frequency modulation resonance analysis. The above-described literature shows that the envelope analysis is an effective method for the fault diagnosis of rolling bearings. With the traditional envelope analysis, a bearing fault can be inspected by the peak value of an envelope spectrum. For obtaining an envelope signal, a band-pass filter with an appropriate central frequency and the frequency interval needs to be decided from experimental testing which yields subjective influences on the diagnosis results\textsuperscript{[6]}. Recently, a new signal analysis method called the empirical mode decomposition (EMD) has been brought out by Huang\textsuperscript{[7]}. The EMD is a self-adaptive signal analysis method which is based on the local time scale of the signal and decomposes a multi-component signal into a number of intrinsic mode functions (IMFs). Each IMF represents a mono-component function versus time. The spectral band for each IMF ranges from high to low frequency and changes with the original signal itself. Therefore, the EMD is a powerful signal analysis method for treating non-linear and non-stationary signals. In applications, the EMD has been successfully applied to numerous investigation fields, such as acoustic, biological, ocean, earthquake, climate, fault diagnosis, etc\textsuperscript{[8]}. Moreover, the EMD associated with other techniques like the wavelet packet transform, the energy operator demodulation, the support vector machine and the Teager Kaiser energy operator has also been applied to assist in bearing fault diagnosis\textsuperscript{[9–12]}. It is found some
studies [13–15] performed combining the EMD with the envelope analysis as a detection tool for the diagnosis of sole bearing fault. As to a bearing with multiple faults, McFadden and Smith [16] first extended from a single point defect model and developed a model for describing high-frequency vibration produced by multiple point defects on the inner race of a rolling element bearing under radial load. It is noted [17–22] that signal analysis methods such as wavelet denoising or EMD, together with feature classification or pattern recognition techniques like support vector machine, neuro-fuzzy classifier, or hidden Markov model were frequently employed as tools for the diagnosis of a multi-fault bearing. But, those supervised pattern recognition approaches with a prior-collected data base made the fault detection impractical, and the diagnosis process hard be applied in industry.

This study aims to propose a more feasible diagnosis process for multi-fault bearings through using appropriate IMFs for subsequent envelope analysis. However, the procedure for selecting an appropriate IMF (or more) to characterize bearing-fault signatures has not been explored and addressed yet. It is noted that IMF 1 after the sifting of EMD was always used in the envelope analysis without explanation. Moreover, when the conventional envelope analysis was used alone to detect bearing faults, all the resonant frequency bands need to be examined, i.e., to band-filter the measured signal for each resonant frequency before taking the envelope analysis. This made the fault detection task tedious and time-consuming. This paper demonstrates the procedure with a new concept that is to compare the spectra of sifted IMFs with the spectrogram of measured vibration response resulting from a swept-sine excitation. The IMF with a concurrent resonance frequency band is selected for the subsequent envelope analysis of rolling-bearing fault detection. Then, the bearing fault signatures can be characterized. As examples, both the cases of dual-fault and triple-fault bearings are considered and used to justify the proposed idea. Further, this detection procedure superior to the conventional envelope analysis in the multi-fault bearing diagnosis is compared and discussed.

2. Experimental setup

A bearing-fault test rig consisting of a servo-motor, a coupling, and a shaft with two rotor disks and two ball bearings (ASAHI UCP-204) with seats, is shown in Fig. 1. Various machine fault types, such as unbalance, misalignment and bearing faults, can be created and tuned using this platform. In this paper, the platform was employed to investigate bearing-fault detection techniques. Some bearing geometric parameters are the number of rolling balls, \( n = 8 \), the contact angle, \( \alpha = 0^\circ \), the ball diameter, \( d = 7.8 \) mm and the pitch diameter, \( D = 33.5 \) mm. Two accelerometers were mounted on the bearing seats to measure vibration signals translating to the bearings. The digital tachometer was used to measure the shaft speed.

In the experiments a sound bearing was mounted on the left-hand-side, and the other side was a bearing with different conditions (normal, dual faults and triple faults). Fig. 2 illustrates a normal bearing, a dual-fault bearing with an outer-race defect (1-mm diameter hole) and an inner-race defect (a slot of 0.2-mm width and 1-mm depth), and a triple-fault bearing with a ball and cage defect (1-mm diameter hole) and an inner-race defect (a slot of 0.2-mm width and 1-mm depth). During the data acquisition to detect bearing faults, the motor speed kept stationary around 1500 rpm, or the rotation frequency, \( f_r = 25 \) Hz. Additionally, the data acquisition system includes an anti-aliasing filter and a DAQ Card (NI-6024E). The sampling frequency and the data-acquiring time were 20 kHz and 1 s, respectively.

3. Proposed procedure to detect bearing faults

This study proposes a detection procedure exploiting the nature of IMFs for rolling-bearing fault diagnosis. As the decomposed IMFs through the EMD computation possess the characteristics of band-pass filtering, combining the EMD with a swept-sine excitation is able to select an appropriate IMF that contains a resonance frequency band modulating the defect feature frequency. This frequency exhibiting a specific faulty condition can be eventually characterized by the envelope analysis.

3.1. Empirical mode decomposition method: a sifting process

The empirical mode decomposition is an adaptive signal decomposition method, which is able to decompose non-linear and non-stationary data into a sequence of amplitude-modulation/frequency-modulation (AM/FM) components or alike. These independent components to be obtained are called intrinsic mode functions, which must satisfy the two conditions [7]: (1) In the whole set data, the number of extrema and the number of zero-crossings must either be equal or different at most by one. (2) At any point, the mean of the envelope defined by local maxima and the envelope defined by the local minima are zero.

The decomposition procedure of EMD called the sifting process is briefly described below [8,9].

(1) Find out all the local extrema, \( Е_{max}(t) \), and then couple with all the local maxima by a cubic spline as the upper envelop, \( u(t) \).
(2) Repeat the procedure (1). The local minima, \( Е_{min}(t) \) produces the lower envelope, \( l(t) \).
(3) Compute the local mean, \( m(t) = (u(t) + l(t))/2 \).
(4) Subtract \( m(t) \) from the original signal, \( x(t) \), and then the first component, \( h_1(t) \), can be obtained. If \( h_1(t) \) satisfies the condition of IMF, \( h_1(t) \) is designed as \( c_1(t) \).

![Fig. 1. Ball-bearing fault test rig with two rotors.](image-url)
By the sifting iterative operation, $x(t)$ can be decomposed into $N$ empirical mode functions and a residue, $r(t)$. Thus, the original signal can be represented as $x(t) = \sum_{i=1}^{N} c_i(t) + r(t)$. The decomposition process will stop as soon as $r(t)$ becomes a monotonic function or a constant, from which no more IMF can be extracted.

3.2. Selecting criterion of resonance frequency bands

In this study, the decomposed IMFs associated with the envelope analysis are employed to diagnose the incipient failure of bearings. After compared with the resonance bands characterized from the measured signal along with run-up bench excitation, a specific IMF provides the choice of resonance frequency bands for the subsequent envelope analysis. Namely, a specific IMF (or more) is selected to proceed with the envelope analysis, where a concurrent frequency band with relatively intense energy occurs at both the spectrum of a sifted IMF and the spectrogram of measured vibration response from a run-up excitation. It is known that a measured dynamic signal can be decomposed into quite a few IMFs; and the feature signatures of a bearing fault such as the inner-race, outer-race or ball/roller defect are embedded in one or a few IMFs if the mounted accelerometer is close enough to the defects so as to pick up the feature signatures. The study explicitly shows how an appropriate IMF is selected to diagnose machine element faults. To the best of our knowledge, this procedure has not been conveyed in the field of machine fault diagnosis yet. The proposed procedure with this insight concept as shown in Fig. 3 can be described below.

(1) The resonance frequencies of bearing components can be acquired as an accelerometer is used and mounted on the bearing seat. Due to the swept excitation through running up a rotary machine, the resonance frequency bands of the mechanical system can be characterized by the spectrogram of a measured signal.

(2) During a stationary revolution of the machine the vibration signal measured from the bearing can be decomposed into a series of IMFs by the EMD method.

(3) The modulation signature that the feature frequencies of defects are embedded in is decided according to the concurrent frequency band in step (1) and (2). Thus an IMF (or more IMFs) containing the modulation signature is selected appropriately.
The analytic signal $a_i(t)$ of a selected IMF is computed by using Eq. (2) in Section 3.3 and then the envelope spectrum of $a_i(t)$ is further obtained. Eventually, the feature frequency of the bearing fault can be characterized in the spectrum.

### 3.3. Envelope analysis

The envelope analysis is a well-known method to extract periodic impacts from the vibration signals of machinery. After using the EMD to obtain a series of IMFs and selecting an appropriate IMF through the proposed procedure, we can proceed with the envelope analysis to extract the feature frequency of a bearing fault. Otherwise, for the conventional envelope analysis the signal to be processed first needs to be band-pass filtered properly to enhance the bearing-fault frequency.

Apply Hilbert transform to a selected IMF, $c_i(t)$, the conjugate part of its analytical form can be obtained as

$$H[c_i(t)] = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{c_i(t)}{t-t'} dt.$$  \hspace{1cm} (1)

Thus, the analytic signal $z_i(t)$ can be expressed as

$$z_i(t) = c_i(t) + jH[c_i(t)],$$ \hspace{1cm} (2)

which can also be expressed in a complex form

$$z_i(t) = a_i(t) \exp(j\omega_i(t)),$$ \hspace{1cm} (3)

where $a_i(t)$, namely, the envelope of $z_i(t)$, is computed with

$$a_i(t) = \sqrt{c_i^2(t) + H^2[c_i(t)].}$$ \hspace{1cm} (4)

Then $a_i(t)$ is further treated by taking Fourier transform to obtain the envelope spectrum being able to single out bearing fault features. The procedure regarding the envelope analysis is described in Fig. 4. It is worth mentioning that it is not practical to use numerical integration for obtaining Hilbert transform (Eq. (1)) due to the singularity problem; instead, to employ the property of the spectrum of an analytic signal. Actually, the analytic form of a signal, $c_i(t)$ here, is computed by taking inverse Fourier transform of the spectrum of $c_i(t)$ with setting null to the amplitude of negative frequency and doubling the amplitude of positive frequency [23].

### 4. Experimental results and discussions

Generally, vibration signals of a bearing that mainly arise from the varying compliance of structural, internal excitation and external disturbance are complex and nonlinear. The feature frequencies of the bearing are usually masked in the background noise. Thus the detection of bearing faults is uneasy. In some cases, perhaps a gearbox is a part of a mechanical system. To monitor and diagnose machine component conditions, accelerometers are usually mounted on the housing and/or the bearings of input/output shafts. Thus, beside the bearing fault signatures the speed-related signal components arising from gear meshing and excited housing-resonance signals are all captured by the measurement system. The bearing fault signals are not hard to be discriminated from resonance frequencies generated by the
bearing and other structures/components when compared through the spectrograms characterized in a time–frequency (or rpm-frequency) plane. In this section, both the traditional envelope analysis and the proposed procedure are used to detect various bearing faults; and the diagnosis outcomes will be compared and discussed.

Fig. 6. Data from a normal bearing. (a) Spectrogram to characterize resonance frequency bands of structure; (b) envelope spectrum with a pass band between 6500 and 7500 Hz; (c) computed waveforms and (d) Fourier spectra of the first four IMFs; envelope spectra of (e) IMF 1 and (f) IMF 3.
4.1. Normal bearing

Proceeding with the bearing fault diagnosis is first to measure the vibration behavior of a sound ball bearing. It is found in Fig. 5 that only the rotation frequency, 25 Hz, corresponding to a stationary revolution with a speed of 1500 rpm and its higher harmonics are present in the spectrum of a measured vibration signal. Moreover, its envelope spectrum cannot single out any fault frequency (Fig. 6(b)). The spectrogram (Hanning window length 4096 and overlap 97%, the same afterwards) of an acquired measurement resulting from run-up excitation characterizes the resonance frequency bands of the system, around 2000, 4000 and 7200 Hz, respectively, as shown in Fig. 6(a). According to the proposed procedure, the spectra of the first four IMF components are illustrated in Fig. 6(d); and compared with Fig. 6(a), their concurrent frequency bands are all at about 2000, 4000 and 7200 Hz. Here, IMFs 1 and 3 were selected and used to diagnose bearing conditions. The envelope spectra of IMFs 1 and 3 (Fig. 6(e) and (f)) show no evident bearing faults except rotation frequency component (25 Hz) and its higher harmonics. It is worth noted that as shown in Fig. 6(a) and (d), low-frequency noise around 1000 Hz and below with intense energy exists arising from the excitation of test bench during measurement. This may introduce unwanted artifacts in the envelope spectrum of a sifted IMF, such as the spectrum shown in Fig. 6(f). Thus, such an IMF can be ignored, especially in case multiple IMFs are selected.

In this normal-condition case, both the conventional envelope analysis and the proposed procedure show only the rotation frequency of the shaft, but no feature frequencies of bearing faults. It is clear that the bearing is in a healthy condition.

4.2. Bearing with dual faults

The feature frequencies of a ball bearing with outer-race and inner-race defects can be computed by the following formula [24]

\[ f_{outer} = \frac{N}{2} \left( 1 + \frac{d}{D} \cos \alpha \right) f_r, \]

and

\[ f_{inner} = \frac{N}{2} \left( 1 + \frac{d}{D} \cos \alpha \right) f_r, \]

where \( d \) is the diameter of the ball, \( N \) is the numbers of the ball, \( D \) is the pitch circle diameter of the rolling bearing, \( x \) is the contact angle of the rolling bearing, and \( f_r \) is the rotation frequency of the shaft.

In this case, the feature frequency, \( f_{outer} \) and \( f_{inner} \), obtained from Eqs. (5) and (6) are 76.7 Hz and 123.3 Hz, respectively, while the rotor system runs at 1500 rpm. Fig. 7 shows the original vibration signal of the bearing with dual faults. From observing its spectrum, only the shaft-speed frequency, 25 Hz, and its higher harmonics are shown while the feature frequencies of outer-race and inner-race defects cannot be singled out.

The spectrogram of response waveform measured from run-up excitation with the dual-fault bearing is illustrated in Fig. 8(a), which characterizes the resonant-frequency bands of the structure at about 400, 4000, and 7500 Hz, respectively. For proceeding with the conventional envelope analysis, all four resonance bands need to be examined for the bearing-fault detection. That is, the vibration signal measured at the speed of 1500 rpm is band-pass filtered with a center-frequency shown above, and is subsequently taken the envelope analysis. In this case, the first and second resonant frequencies, i.e. 400, and 4000 Hz, which the faulty frequency is not modulated by, cannot be used as the center-frequency of a band-pass filter to diagnose the bearing fault. Conversely, the envelope analysis of the band-pass filtered signal using 7500 Hz as the center frequency and the pass band of 7000 and 8000 Hz, can single out the feature frequencies, \( f_{outer} \) and \( f_{inner} \), of the outer-race and the inner-race faults bearing, as shown in Fig. 8(b).

According to the proposed procedure, Fig. 8(c) and (d) shows the waveform and spectra of the first five decomposed IMFs computed by the EMD. By comparing Fig. 8(a) with Fig. 8(d) their concurrent frequency band is around 7500 Hz. The resonant-frequency band sits on IMF 1, and thus IMF 1 is selected to

![Fig. 7. Time-waveform along with its spectrum measured from a dual-fault (inner and outer) bearing with the test rig running at 1500 rpm.](image-url)
diagnose bearing faults. It is found the feature frequencies, $f_{outer}$ and $f_{inner}$, of the outer-race and the inner-race defects are clearly characterized in Fig. 8(e). It is worth noting that the feature frequencies of the outer-race and the inner-race defects can be characterized in both Fig. 8(b) and (e). Moreover, the amplitude of the feature frequency at the inner-race defect is higher than that

![Time-frequency spectrum of Rotor system](image1)

![Envelope Spectrum](image2)

**Fig. 8.** Data from a dual-fault (inner and outer) bearing. (a) Spectrogram to characterize resonance bands of structure; (b) envelope spectrum with a pass band between 7000 and 8000 Hz; (c) computed waveforms and (d) Fourier spectra of the first five IMFs; (e) envelope spectrum of IMF 1.
of the outer-race one due to the radial load of shaft. As a comparison, an improper IMF, such as IMF 4 with a 2000-Hz spectral band, was selected for bearing fault diagnosis. It is observed that the frequency band around 2000 Hz in the spectrogram of measured response resulting from run-up excitation is not as clear and strong as others. The envelope spectrum of IMF 4 only characterizes the feature frequency of inner-race fault, as shown in Fig. 9. As to the selection of a proper IMF, a general rule is that a concurrent frequency band with relatively intense energy occurs both at the response of run-up excitation and an extracted IMF, and thus this IMF is selected and applied to diagnose bearing conditions.

4.3. Bearing with triple faults

The feature frequencies of a ball bearing with triple defects, inner-race, cage and ball, respectively, can be computed by the following formula while the outer-race is fixed [24].

\[
f_C = \frac{1}{2} \left( 1 - \frac{d}{D} \cos \alpha \right) f_r, \tag{7}
\]

\[
f_{r\text{iso}} = \frac{1}{2} \left( 1 + \frac{d}{D} \cos \alpha \right) f_r, \tag{8}
\]

\[
f_B = \frac{D}{2d} \left( 1 - \frac{d^2}{D^2} \cos^2 \alpha \right) f_r, \tag{9}
\]

and

\[
f_{re} = \frac{D}{d} \left( 1 - \frac{d^2}{D^2} \cos^2 \alpha \right) f_r, \tag{10}
\]

where \(f_C, f_{r\text{iso}}, f_B \) and \(f_{re} \) denote the rotation frequency of cage, the relative rotation frequency between cage and inner-race, the self-spinning frequency of ball, and the revolution frequency of ball along the shaft, respectively. The feature frequencies, \(f_C \) and \(f_{r\text{iso}} \), are concerned with the cage fault of a bearing, and the others, \(f_B \) and \(f_{re} \), relate to the ball fault of a bearing. Therefore, the designated triple faults of a ball bearing may yield five feature frequencies, i.e., \(f_C, f_{r\text{iso}}, f_B, f_{re} \) and \(f_{inner} \). In this case, substituting bearing parameters into the five feature frequencies, \(f_C, f_{r\text{iso}}, f_B, f_{re} \) and \(f_{inner} \), Eqs. (6)-(10), we can have 9.6, 15.4, 50.8, 101.8 and 123.3 Hz, respectively, with the test rig running at 1500 rpm. Fig. 10 shows the measured vibration signal of the bearing with triple faults. Again, alike the dual-fault case, only the revolution-speed frequency of the shaft and its higher harmonics are illustrated in the spectrum without the feature frequencies of triple faults.

The spectrogram of response waveform measured from the run-up excitation of the test rig with a triple-fault bearing is shown in Fig. 11(a), which characterizes the resonant-frequency

![Fig. 9. Envelope spectrum of IMF 4 decomposed from the vibration signal with the test rig running at 1500 rpm.](image)

![Fig. 10. Time-waveform along with its spectrum measured from a triple-fault (inner, cage and ball) bearing with the test rig running at 1500 rpm.](image)
bands of the structure at about 400, 2000, 4200, and 7300 Hz, respectively. If using the envelope analysis, one needs to inspect all the bands. In the case, the envelope analysis of the band-pass filtered signal using a center frequency at 2000 Hz can enhance the four feature frequencies, $f_c, f_{rcisof}, f_{ref}$ and $f_{inner}$, of a triple-fault bearing, as shown in Fig. 11(b).

Fig. 11. Data from a triple-fault (inner, cage and ball) bearing. (a) Spectrogram to characterize resonance bands of structure; (b) envelope spectrum with a pass band between 1500 and 2500 Hz; (c) computed waveforms and (d) Fourier spectra of the first five IMFs; envelope spectra of a combination of (e) IMF2–IMF4; and (f) IMF1–IMF3.
Likewise, according to the proposed procedure Fig. 11(c) and (d) shows the waveform and spectra of the first five IMFs decomposed by the EMD. By comparing Fig. 11(a) with Fig. 11(d) their concurrent frequency band sits around 2000 Hz. Therefore, all of IMF 2, IMF 3 and IMF 4 satisfying the guidelines are selected. The envelope spectrum of the signal combining IMF 2, IMF 3 and IMF 4, as shown in Fig. 11(e), can identify the triple faults. Here we choose a combination of IMF2, IMF3 and IMF4 for triple-fault diagnosis of bearings due to higher spectral energy (their spectral amplitude over 0.05, as shown in Fig. 11(d)). Actually if using a combination of IMF1, IMF2 and IMF3, we compute its envelope spectrum. It is found triple faults can still be detected, as shown in Fig. 11(f), although the characterized roller defect is not as clear as using the combination of IMF2, IMF3 and IMF4. It is noted as bearing balls pass by a cage defects rather lightly, the amplitudes of feature frequencies, \( f_c \) and \( f_{ciso} \) of cage fault are relatively small compared with others, as shown in Fig. 11(b), (e) and (f). Again, if a wrong IMF was selected such as IMF 5, its envelope spectrum hardly characterizes the feature frequencies of triple faults and their higher harmonics (see Fig. 12). This example shows that the component IMF 5 is not always helpful to identify bearing faults although using the envelope analysis.

5. Conclusions

This study tries to propose guidelines on selecting appropriate IMF(s) to proceed the envelope analysis for the diagnosis of multiple bearing faults, and further applied for the diagnosis of other transmission elements. From all these verified experiments and examining discussions, some practical rules are summarized below.

1. Those IMFs with a concurrent frequency band which also occurs in the response of run-up excitation can be selected for subsequent envelope analysis.
2. If more than one IMF can be selected, it is suggested that the IMF with relatively intense-energy concurrent frequency band is considered, or a combination of several IMFs is applied.
3. If a selected IMF with intense noise arising from the excitation of test bench, the noise may introduce unwanted artifacts in the envelope spectrum of a sifted IMF. Such an IMF can be ignored.

Additionally, an enumerated summary regarding the multiple-fault diagnosis of ball bearings can be made below.

1. Experiments in this study have demonstrated that the proposed procedure using an appropriate IMF or several IMFs is superior to the approach using the conventional envelope analysis which needs to examine all resonant frequency bands.
2. The proposed method when applied in industry or workshops is particularly practical compared with the diagnosis procedure using a combination of signal analysis and subsequent feature extraction/pattern recognition [17–22].
3. Comparing with some ball-bearing fault detection studies [13,14], this paper proposes a reasonable and appropriate procedure to select a decomposed IMF (or more) for the multiple fault diagnosis of bearings, instead of using always IMF 1 (Fig. 11(e) and (f)).
4. In Du and Yang’s study [15], IMF 2 with both high-level vibration and impulses in the waveform was chosen. It is noted that to judge the waveform being impulsive is sometimes subjective. In this paper, the first four IMFs, IMF 1, 2, 3, and 4 (Fig. 8(c), look possessing an impulsive nature for the case of dual fault; and again, the first four IMFs, IMF 1, 2, 3, and 4 (Fig. 11(c)), for the case of triple faults. Here, we try to propose objective guidelines for choosing appropriate IMFs to detect bearing faults. The proposed procedure can effectively detect the multiple faults of a bearing (Figs. 8(e) and 11(e)).

References


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