An insight concept to select appropriate IMFs for envelope analysis of bearing fault diagnosis

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ABSTRACT

Traditional envelope analysis must examine all the resonant frequency bands during the process of bearing fault detection. To eliminate the above deficiency, this paper presents an insight concept based on the empirical mode decomposition to choose an appropriate resonant frequency band for characterizing feature frequencies of bearing faults by using the envelope analysis subsequently. By the band-pass filtering nature of the empirical mode decomposition, the resonant frequency bands are allocated in a specific intrinsic mode function. The inner or outer ring of bearings scratched intentionally is used to validate the feasibility of the proposed idea, and comparisons with the traditional envelope analysis are addressed. The experimental results show that the proposed insight concept can efficiently and correctly diagnose the bearing fault types.

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1. Introduction

Rolling bearings are important components in rotating machines. They are used in many fields, such as machine tools, motors, and turbo-pumps. However, bearing faults are a common cause of the breakdown of machines. For reducing machinery downtime, the fault diagnosis of rolling bearings is crucial. Fault detection techniques of roller bearings, such as vibration, acoustic, and temperature measurements, have been investigated recently. Among these, the vibration measurement and analysis are extensively employed. When bearing faults occur, vibration signals exhibit an amplitude modulation phenomenon that combines the characteristic frequency of the bearing defect with the structural resonance of systems. Therefore, many detecting methods are devoted to the research of the demodulation resonance analysis, especially in the enve-lope analysis technique. It was presented in the early 1970s by Mechanical Technology Inc. [1] and originally called the high frequency resonance technique [2], and was widely applied in the fault diagnosis of rolling bearings. Donelson III and Dicus [3] employed the envelope analysis to detect bearing faults of the large-sized vehicle; the vibration and acoustic signals were measured for analyzing different types of the bearing defects. Hochmann and Bechhoefer [4] applied the envelope analysis in the diagnosis of helicopter bearings. To detect bearing faults of a two-sided rotor platform and a high-speed cutting machine, Chu [5] applied the traditional envelope analysis in the band-pass filtered signals, where appropriate filter bands were chosen by the excitation of speeding up machines. Additionally, McInerny and Dai [6] developed a module on the bearing diagnostics by the graphical user interface of MATLAB which relied on the traditional spectral analysis and the envelope analysis.

The literature described above 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

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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 [7]. In the recent years, a new time–frequency analysis method called the Hilbert–Huang transform (HHT) was brought out by Huang et al. [8]. The HHT includes two procedures, namely, the empirical mode decomposition (EMD) and the Hilbert spectrum analysis (HSA). 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, and fault diagnosis [9]. 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 [10–13]. It is found some studies [14–17] combined the EMD with the envelope analysis as a detection tool for the bearing fault diagnosis.

However, how to select an appropriate IMF for subsequent envelope analysis to characterize bearing faults has not been explored and addressed in the above literatures. It is noted that the component of IMF 1 was always used in the envelope analysis subsequently without any explanation. Moreover, when the conventional envelope analysis was used along to detect bearing faults, all the resonant frequency bands need to be examined. Therefore, the above approaches are not suited for practical applications. This paper demonstrates the procedure with an insight concept that combines the EMD with a swept-sine excitation to select a resonance frequency band (or more) for the subsequent envelope analysis of rolling-bearing fault detection. As examples, both the outer-race and the inner-race faults are considered and used to justify the proposed idea. Further, this detection procedure superior to the conventional envelope analysis in the bearing fault diagnosis is compared and discussed.

2. Experimental setup

An experiment test bench, including a servo-motor, a coupling, and a shaft with two rotor-disks and two ball bearings (ASAHI UCP-204), is shown in Fig. 1. Various fault types, such as unbalance, misalignment and bearing faults, can be created using this platform. In this paper, the platform was employed to investigate bearing-fault detection techniques. The geometric parameters of the bearing are the number of rolling balls, $n = 8$, the contact angle, $\alpha = 0°$, 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 experimentation the left-hand-side bearing remained normal, and the other one varied with different conditions (normal, inner-race and outer-race faults). Fig. 2 illustrates a normal bearing, an outer-race-defect bearing with 1-mm diameter hole, and an inner-race-defect bearing with 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, including a low-pass filter and DAQ Card (NI-6024E) was used to acquire measurement data. The sampling frequency and the data-acquisition period were 20 kHz and 1 s, respectively.

3. Proposed procedure to detect bearing faults

This study proposes a detection procedure for rolling-bearing fault diagnosis. An insight concept is exploited as the decomposed IMFs through the EMD computation possess a band-pass filtering nature. Combining the EMD with a swept-sine excitation is able to select an appropriate IMF that contains a resonance frequency band modulating the defect characteristic 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
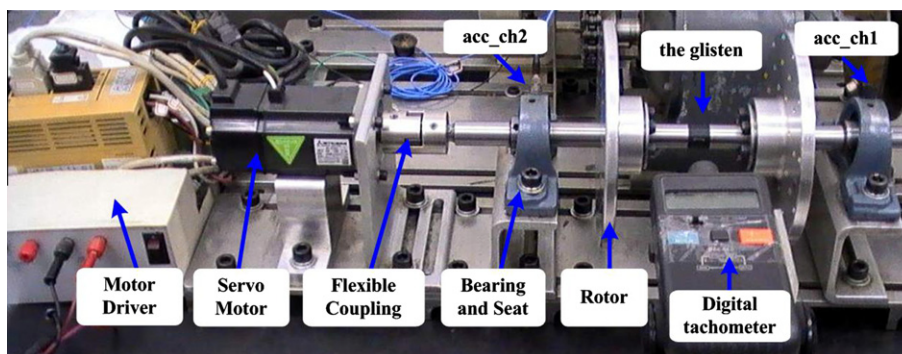

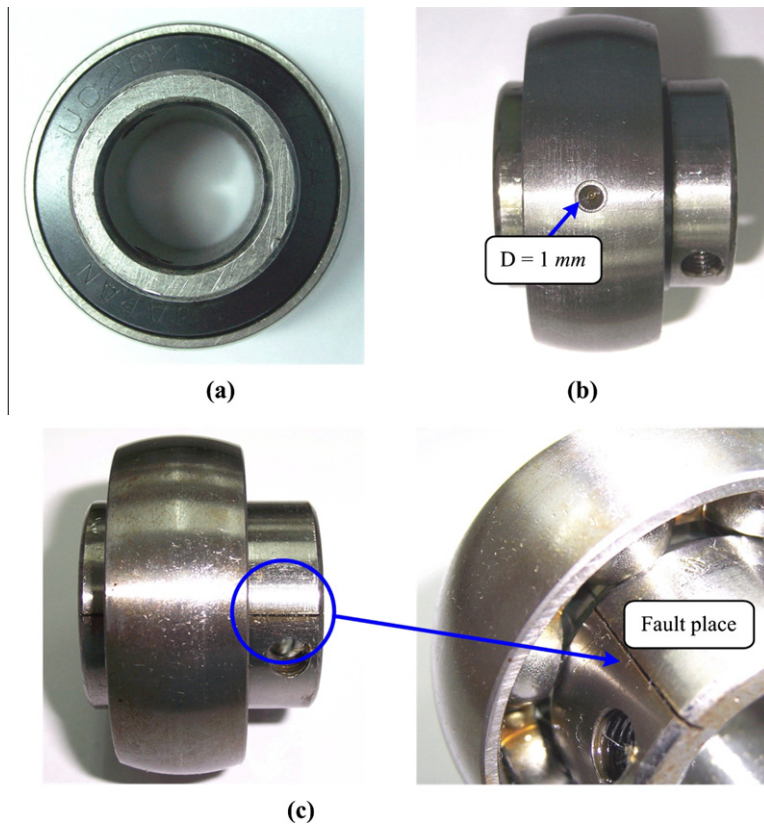**Fig. 1.** Experimental setup with a set of two-sided rotor.

Fig. 2. Bearing with different faults: (a) normal, (b) outer-race fault, and (c) inner-race fault.
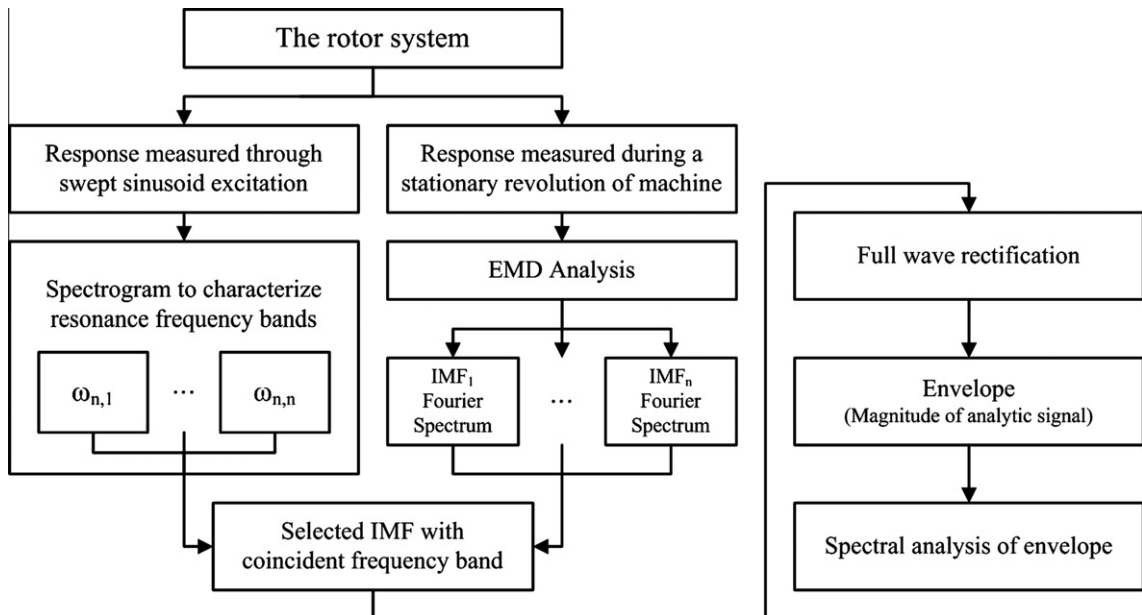

Fig. 3. Procedure to diagnose bearing faults using selected IMFs.

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 conductions [8]: (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 (SP) is briefly described below [8,9].

(1) Find out all the local extrema, $E_{max}(t)$, 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, $E_{min}(t)$, 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 $c_1(t)$.
(5) By the sifting iterative operation, $x(t)$ can be decomposed into N imperial mode functions and a residue, $r(t)$.

Thus, the original signal can be represented as $x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t)$. 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 *coincident* frequency band also occurs in the measured signal obtained from the 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.
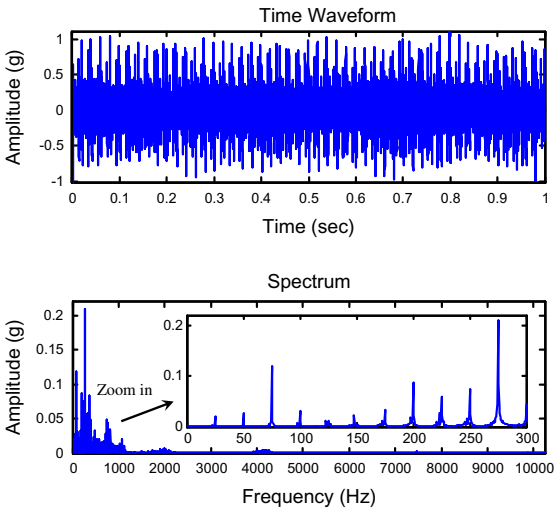

Fig. 5. Time-waveform along with its spectrum measured from a normal bearing running at 1500 rpm.
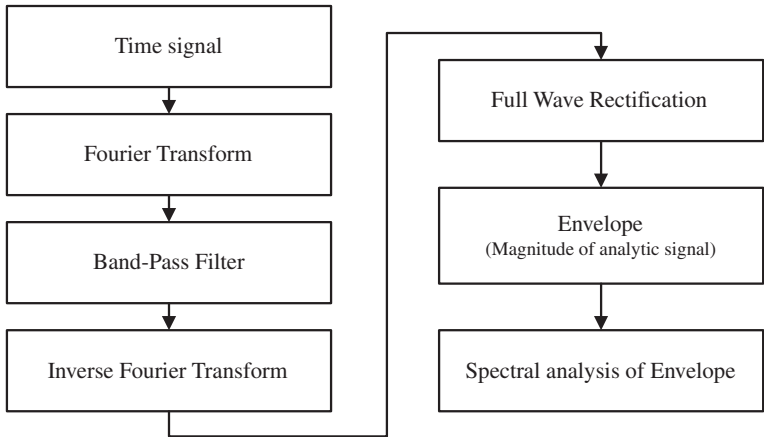

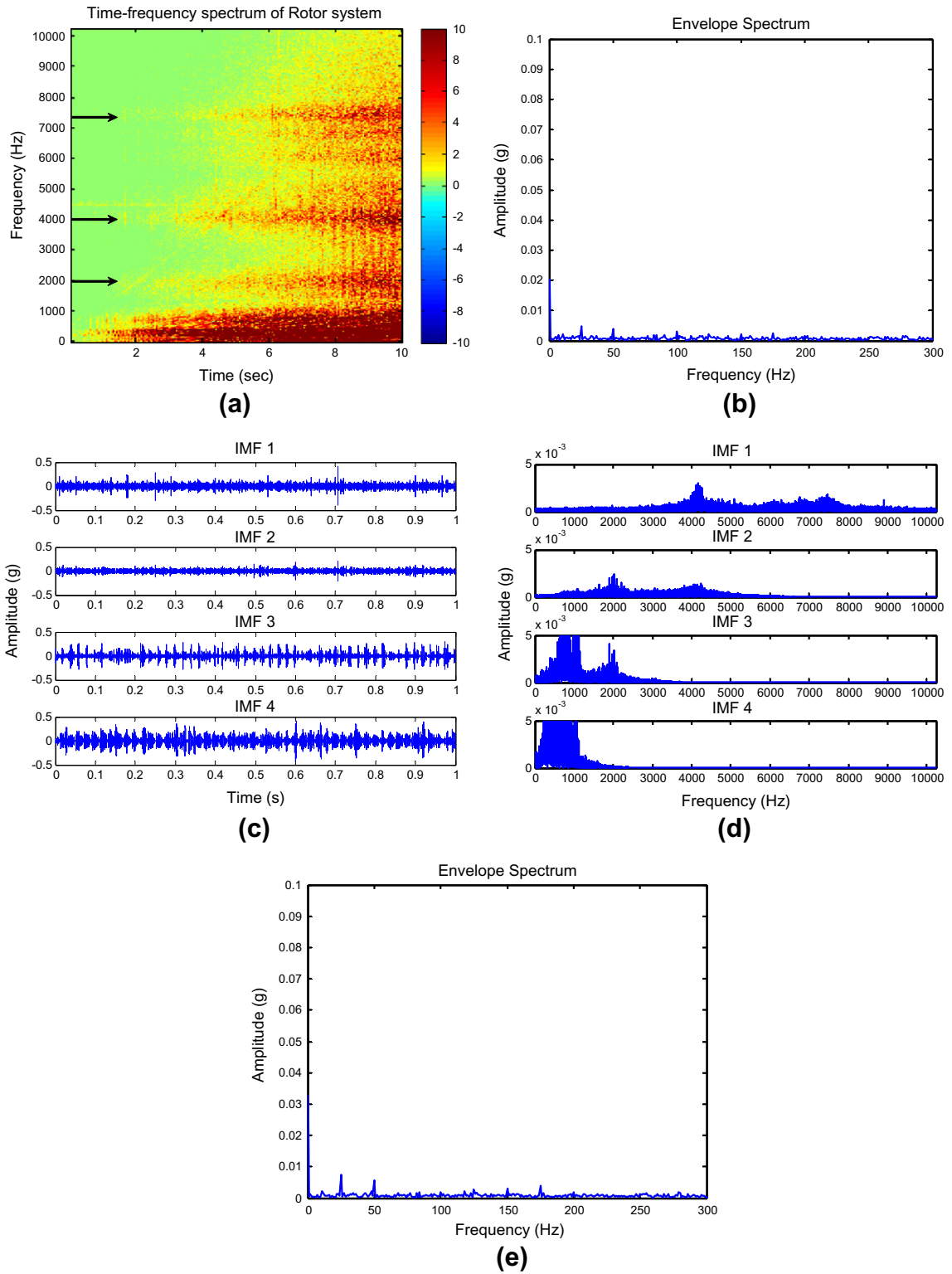**Fig. 4.** Flowchart of the envelope analysis.

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; (e) envelope spectrum of IMF 1.

(3) The modulation signature that the feature frequencies of defects are embedded in is decided according to the coincident frequency band in step (1) and (2). Thus an IMF (or more IMFs) containing the modulation signature is selected appropriately.

(4) 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 characteristic 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 an selected IMF, $c_i(t)$, the conjugate part of its analytical form can be obtained as

$$H[c_i(t)] = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{c_i(\tau)}{t - \tau} d\tau. \qquad (1)$$

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

$$z_i(t) = c_i(t) + jH[c_i(t)], \qquad (2)$$

which can also be expressed in a complex form

$$z_i(t) = a_i(t) \exp(j\omega_i(t)), \qquad (3)$$

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

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

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 [18].

4. Experimental results and discussion

Generally, vibration signals of a bearing that mainly arises from the varying compliance of structural, internal excitation and external disturbance are complex and non-linear. The feature frequencies of the bearing are usually masked in the background noise. Thus the detection of bearing faults is rather difficult. 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, the speed-related signatures arising from gear meshing and excited housing-resonance signal components are acquired. They are not hard to be discriminated from resonance frequencies generated by the bearing of interest to be detected 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 performance will be compared and discussed.

4.1. Normal bearing

Proceeding with the bearing fault diagnosis is first to measure the vibration behavior of a sound 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. 6b). 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. 6a. According to the proposed procedure, the spectra of the first four IMF components are illustrated in Fig. 6c; and compared with Fig. 6a, their coincident frequency bands are at about 4000 and 7200 Hz. Therefore, IMF 1 was selected and used to detect bearing faults. It is noted that the envelope spectrum of IMF 1 (Fig. 6d) shows no evident bearing faults except slight rotation frequency component (25 Hz).

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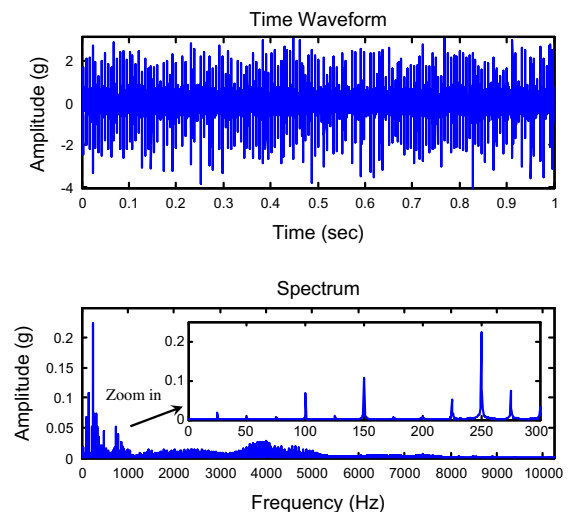

Fig. 7. Time-waveform along with its spectrum measured from an outer-race-fault bearing with the rotor system running at 1500 rpm.
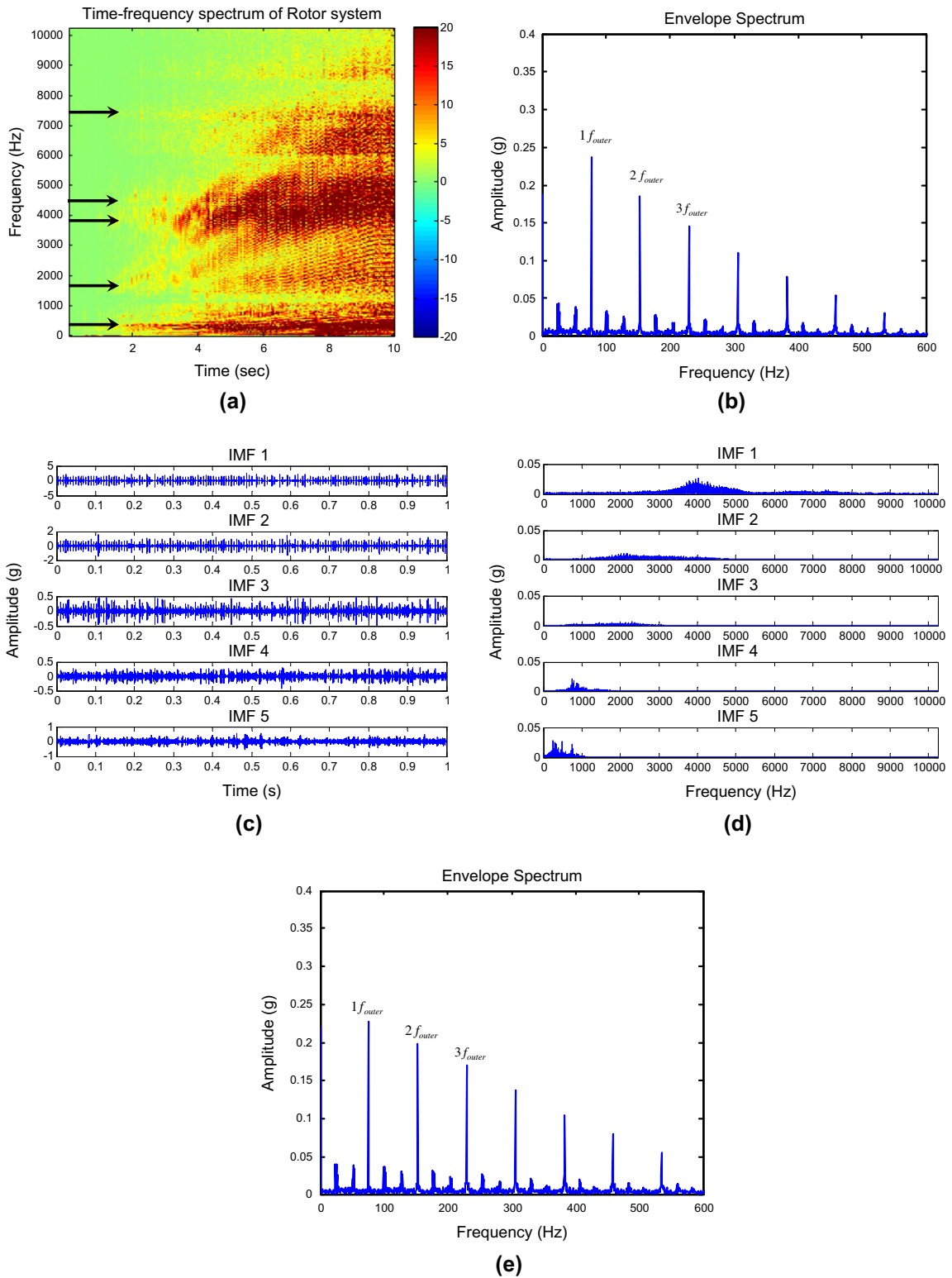
Fig. 8. Data from an outer-race-fault bearing: (a) spectrogram to characterize resonance bands of structure; (b) envelope spectrum with a pass band between 3500 and 4500 Hz; (c) computed waveforms and (d) Fourier spectra of the first five IMFs; (e) envelope spectrum of IMF 1.

4.2. Outer-race fault

The characteristic frequency of an outer-race fault can be calculated through the following equation

$$f_{outer} = \frac{N}{2}\left(1 - \frac{d}{D}\cos\alpha\right)f_r, \tag{5}$$

where d is the diameter of the balls, N is the number of the balls, D is the pitch circle diameter of the rolling bearing, α is the contact angle of the rolling bearing, and f_r is the rotation frequency of the shaft.

In this case, the characteristic frequency, f_{outer}, of the outer-race fault obtained from Eq. (5) is 76.7 Hz while the rotor system runs at 1500 rpm. Fig. 7 shows the original vibration signal of the bearing with an outer-race fault. From observing its spectrum, only the revolution-speed frequency of the shaft is shown while the characteristic frequency of the outer-race fault cannot be singled out.

The spectrogram of response waveform acquired from run-up excitation with the outer-race fault is illustrated in Fig. 8a, which characterizes the resonant-frequency bands of the structure at about 400, 1800, 4200, 7500, and 8800 Hz, respectively. For proceeding with the conventional envelope analysis, all five resonance bands need to be examined for the detection of the outer-race fault. 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, second, fourth and fifth resonant frequencies, i.e. 400, 1800, 7500, and 8800 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 4000 Hz as the center frequency and the pass band of 3500 and 4500 Hz, can single out the characteristic frequency, f_{outer}, of the outer-race-fault bearing, as showed in Fig. 8b. The above describes the procedure using the conventional envelope analysis for bearing fault diagnosis.

According to the proposed procedure, Fig. 8c and d shows the waveform and spectra of the first five decomposed IMFs computed by the EMD. By comparing Fig. 8a with d their coincident frequency band is around between 3500 and 4500 Hz. The resonant-frequency band sits on IMF 1, and then IMF 1 is selected to diagnose bearing faults. It is found the characteristic frequency, f_{outer}, of outer-race fault is clearly characterized in Fig. 8e. Moreover, it is worth noting that the feature frequency of outer-race fault can be characterized in both Fig. 8b and e. As a comparison, if a wrong IMF was selected such as IMF 4, its envelope spectrum shows no outer-race-fault frequency (Fig. 9).

4.3. Inner-race fault

The characteristic frequency of an inner-race fault can be computed through the following equation

$$f_{inner} = \frac{N}{2}\left(1 + \frac{d}{D}\cos\alpha\right)f_r \tag{6}$$

In this case, the characteristic frequency, f_{inner}, of the inner-race fault obtained from Eq. (6) is 123.3 Hz while the
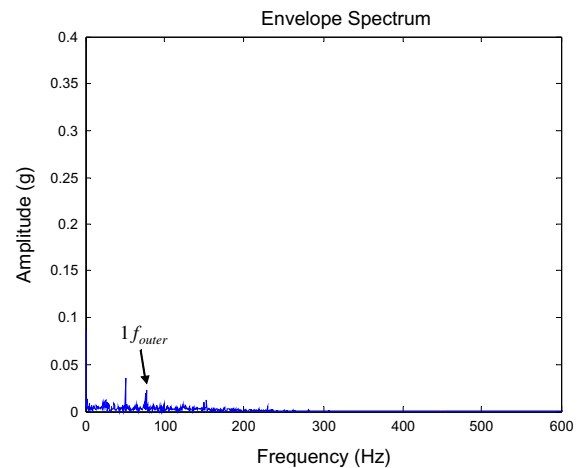

Fig. 9. Envelope spectrum of IMF 4 decomposed from the vibration signal with the rotor system running at 1500 rpm.
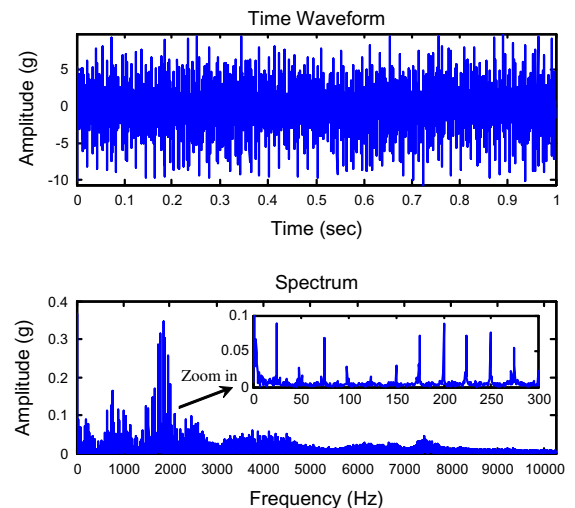

Fig. 10. Time-waveform along with its spectrum measured from an inner-race-fault bearing with the rotor system running at 1500 rpm.

rotor system runs at 1500 rpm. Fig. 10 shows the original vibration signal of the bearing with an inner-race fault. Again, alike as the outer-race-fault case, only the revolution-speed frequency of the shaft and its higher harmonics are shown without the inner-race-fault frequency.

The spectrogram of response waveform acquired from run-up excitation with the outer-race fault is shown in Fig. 11a, which characterizes the resonant-frequency bands of the structure at about 400, 1800, 3800, 4500, and 7500 Hz, respectively. If using the envelope analysis, one needs to inspect all the resonant frequencies. In the case, the envelope analysis of the band-pass filtered signal using a center frequency around 1800 Hz can enhance the characteristic frequency, f_{inner}, of the inner-race-fault bearing, as showed in Fig. 11b.

Likewise, according to the proposed procedure Fig. 11c and d shows the waveform and spectra of the first five
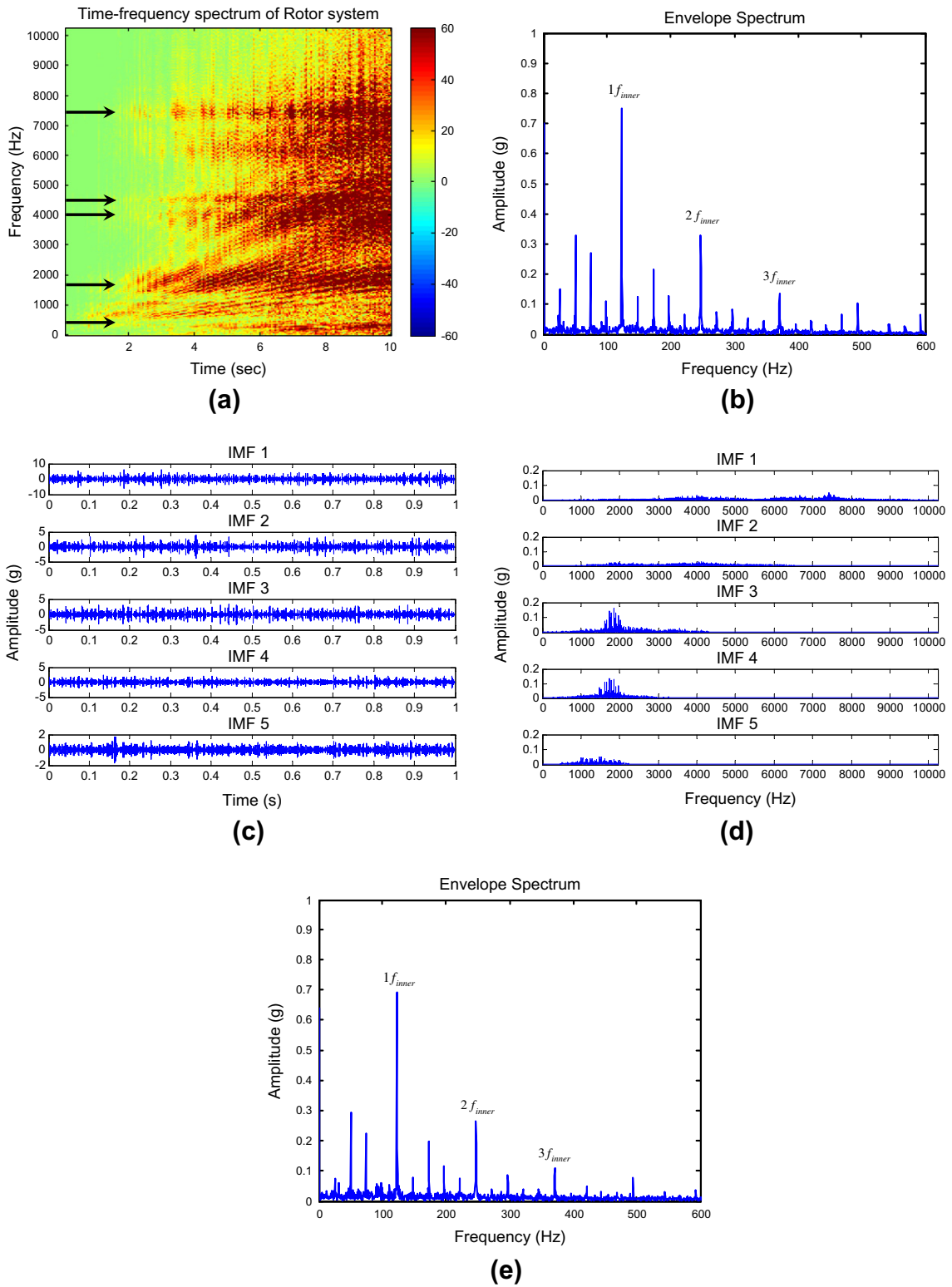
Fig. 11. Data from an inner-race-fault bearing: (a) spectrogram to characterize resonance bands of structure; (b) envelope spectrum with a pass band between 1300 and 2300 Hz; (c) computed waveforms and (d) Fourier spectra of the first five IMFs; (e) envelope spectrum of IMF3-IMF4 combined signal.
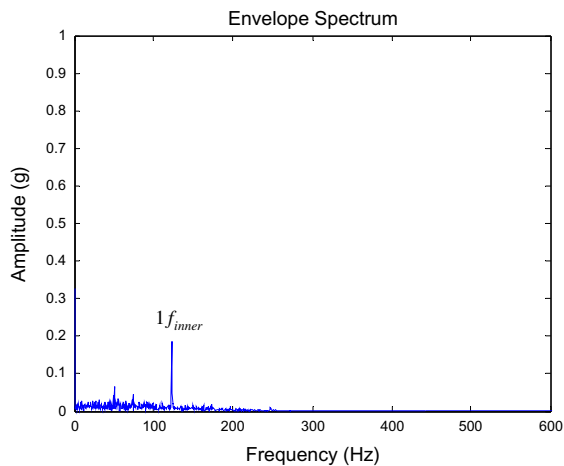
Fig. 12. Envelope spectrum of IMF 5 decomposed from the vibration signal with the rotor system running at 1500 rpm.

IMFs extracted by the EMD. By comparing Fig. 11a with d their coincident frequency band sits around 2000 Hz. Therefore, both IMFs 3 and 4 satisfying the criterion are selected. The envelope spectrum of the signal combining IMF 3 and IMF 4, as shown in Fig. 11e, can characterize the inner-race fault. Again, if a wrong IMF was selected such as IMF 5, its envelope spectrum hardly shows the inner-race-fault frequency and its higher harmonics (see Fig. 12). It is believed that impact-wave trains can be acquired generally while bearing defects exist. This yields the bearing fault frequency and its higher harmonics.

5. Conclusions

Based on the experimental and analysis study presented in this paper, the following conclusions are summarized regarding the bearing fault diagnosis.

1. Experiments in this study have demonstrated that the proposed procedure using an appropriate IMF is superior to the approach using the conventional envelope analysis which needs to examine all resonant frequencies.
2. Compare with some ball-bearing fault detection studies [14–16], this paper proposes a reasonable and appropriate procedure to select a decomposed IMF (or more) for the fault diagnosis, instead of always using IMF 1. In Du and Yang's study [17], 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. 8c), look possessing an impulsive nature for the case of outer-race defect; and again, the first four IMFs, IMF 1, 2, 3, and 4 (Fig. 11c), for the case of inner-race defect. Here, we tried to propose an objective principle for choosing appropriate IMFs to detect bearing faults.

3. The proposed procedure can effectively diagnose the outer-race and the inner-race faults of bearings (Figs. 8e and 11e). Moreover, to further justify this procedure, it is nontrivial to extend the task to multiple-fault bearing diagnosis.

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