Cooling Fan Bearing Fault Identification Using Vibration Measurement

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Abstract—**As a commonly used assembly in computer cooling systems, the normal operation of a cooling fan is critical for guaranteeing system stability and reducing damage to electronic components. Reliability analyses have shown that fan bearing failure is a major failure mode. Therefore, it is necessary to conduct research on fault detection of cooling fan bearings. In this paper we propose vibration-based fan bearing fault detection through the wavelet transform and the Hilbert transform. An experiment on fan bearings was conducted to collect vibration data for the validation of our proposed method. The analysis results show that the proposed method can identify different bearing faults.**

Keywords—cooling fan bearing; fault identification; discrete wavelet transform; Hilbert transform

I. INTRODUCTION

Nowadays, computers are used in many different areas, such as telecommunication, education, manufacturing, marketing, health care, etc. Computer system failure may bring inconvenience in our daily lives, or even cause severe economic losses and catastrophic accidents under certain conditions. The requirement of high operational reliability has driven the research on diagnosis and failure analysis of computer systems. However, it has been a challenging task due to the complicated interactions of system performance parameters and application environments (e.g., temperature, moisture, and vibration) and their effects on system degradation and failure [1].

As a commonly used assembly in a computer cooling system, the mechanical parts of a cooling fan include bearings, shaft, fan blades, and fan housing. A fan is used to move heated air away from the components in the case. According to [2], fan failure is a major problem for many electronic systems. Bearing failure is the top contributor to fan failure.

The normal operation of a cooling fan impacts a computer system by preventing instability, malfunction, and damage to electronic components caused by overheating. Therefore, it is necessary to conduct research on cooling fan bearing fault detection so as to guarantee the normal operation of a fan.

The major type of bearing used in cooling fans is ball bearings, mainly because it has a longer lifespan at higher temperatures (63,000 hours at 50°C) compared to sleeve bearings (40,000 hours at 50°C) [3]. Ball bearings are the fundamental rotating parts in mechanical systems, and much research has been conducted in bearing fault diagnosis [4-8]. However, the literature on computer cooling fan bearing reliability is very limited [2, 9, 10].

It is a challenge to identify ball bearing fault signatures based on vibration signal because the bearing components, including inner race, outer race, cage, and rollers, complicate the bearing vibration signals. When a local fault exists in a ball bearing, the surface is locally affected and the vibration signals exhibit modulation [11]. Therefore, it is necessary to implement filtering and demodulation so as to obtain fault-sensitive features from the raw signals. At present, the Hilbert transform has been widely used as a demodulation method in vibration-based fault diagnosis [12, 13]. It has a quick algorithm and can extract the envelope of the vibration signal. In addition, the wavelet analysis is able to decompose a signal into different scales corresponding to different frequency bandwidths [12, 14, 15], which can be treated as band-pass filters.

The purpose of this study was to investigate fan bearing fault identification methods using vibration measurements that can be used for cooling fan degradation assessment and prognostics. A test rig with a cooling fan was established, with no lubricant in the ball bearing so as to accelerate the experiment. To identify the type of bearing failure from the vibration measurement at the end of experiment, a new method was proposed based on the wavelet and the Hilbert transforms.

This paper is organized as follows. In Section 2, a brief introduction to the wavelet and Hilbert transforms is given. Section 3 presents our proposed method for fan bearing fault identification using the vibration signal. A case study on fan bearings is presented in Section 4, including a description of the experiment and validation of the proposed method. Our conclusions are summarized in Section 5.

II. THEORETICAL BACKGROUND

A. *Wavelet Transform*

The wavelet transform is the time-frequency decomposition of a signal into a set of wavelet basis functions. It possesses flexibility in both the time and frequency domains, and it has

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been widely used in machinery fault diagnosis. The continuous wavelet transform (CWT) of a finite energy time domain signal $x(t)$ with the wavelet $\psi(t)$ is defined as [14]:

$$W(a,b) = \int_{-\infty}^{+\infty} x(t) \frac{1}{\sqrt{a}} \psi^*(\frac{t-b}{a}) dt \tag{1}$$

where $*$ denotes the complex conjugation, $a \in R^+$; $b \in R$; and a and b are the scale and translation parameters, respectively.

As seen in (1), the wavelet coefficient $W(a,b)$ is defined on the $a-b$ plane. A small scale parameter a corresponds to a high-frequency component, and the translation parameter b represents the location of the wavelet basis in the time domain. $W(a,b)$ is a measure of similarity between the signal $x(t)$ and the wavelet $\psi(t)$ at different frequencies determined by the scale parameter a and different time locations determined by the translation parameter b .

Although the CWT offers the possibility of a detailed analysis of transients with an arbitrary fine frequency scale, it is not computationally efficient and it results in high redundancy. The discrete wavelet transform (DWT) is derived from the CWT through discretization of the wavelet, and the most common discretization of the wavelet is based on a power of 2 (i.e., dyadic scales and positions [16]). That is,

$$a = 2^j, b = k2^j, j,k \in Z \tag{2}$$

Therefore, the discrete wavelet function and scaling function can be defined as follows:

$$\psi_{j,k}(t) = 2^{-j/2} \psi(2^{-j}t - k) \tag{3}$$

$$\phi_{j,k}(t) = 2^{-j/2} \phi(2^{-j}t - k) \tag{4}$$

Mallat [16] proposed a fast wavelet decomposition and reconstruction method, which is a classical signal processing scheme, known as a two-channel sub-band coding. In the decomposition process, the signal is convolved with a low-pass filter and a high-pass filter, respectively. It produces two pieces of decomposed signals, namely, the approximation signal and the detail signal. For example, let $x(t) = A_0(t)$; the decomposition process can be repeated as follows:

$$A_{j-1}(t) = A_j(t) + D_j(t) \tag{5}$$

where $A_j(t)$ and $D_j(t)$ are the approximation signal and detail signal at the jth decomposition level, respectively. In reconstruction, a pair of low-pass and high-pass reconstruction filters are convolved with $A_j(t)$ and $D_j(t)$, respectively.

The decomposition of a signal using dyadic orthogonal wavelets is a quadratic sub-band filtering. Suppose a signal is collected at a sampling frequency F_s . The information obtained by DWT on each scale corresponds to a frequency bandwidth $F_s/2^{j+1}$. The frequency band of the approximation A_j is expressed as

$$f_{A_j} \in [0, F_s/2^{j+1}] \tag{6}$$

And the frequency band of the detail D_j is

$$f_{D_j} \in [F_s/2^{j+1}, F_s/2^j] \tag{7}$$

This means that the approximation and detail are the narrow-banded sub-signals of the original signal.

B. *Hilbert Transform*

From a signal processing perspective, the Hilbert transform can be interpreted as a filtering operation in which the amplitude of the frequency component is unchanged, while the phase is shifted by 90°. It is a time-domain convolution that maps one real-valued time-history into another. Given a time domain signal $x(t)$, its Hilbert transform $H[x(t)]$ is defined as:

$$H[x(t)] = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau \tag{8}$$

where t and τ are the time and translation parameters, respectively.

In machinery fault detection, modulation caused by local faults is inevitable in collected signals. In order to identify fault-related signatures, demodulation is a necessary step, and it can be accomplished by forming a complex-valued time-domain analytic signal $A[x(t)]$ with $x(t)$ and $H[x(t)]$. That is,

$$A[x(t)] = x(t) + iH[x(t)] = a(t)e^{i\varphi(t)} \tag{9}$$

where $a(t) = \sqrt{x^2(t) + H^2[x(t)]}$, $\varphi(t) = \arctan \frac{H[x(t)]}{x(t)}$, and $i = \sqrt{-1}$; $a(t)$ is the envelope of $A[x(t)]$, which represents an estimate of the modulation in the signal.

III. THE PROPOSED METHOD FOR FAN BEARING FAULT IDENTIFICATION

A. *Fan Bearing Failure Behavior*

The cooling fan bearings studied in this paper are typical of those used in many computers. Therefore, it is necessary to understand its failure behavior in order to conduct research on fan bearing fault detection. Typical failures of ball bearings include local faults on the inner race, outer race, cage, and rollers. If there is a local fault on a certain part of a ball bearing, the corresponding fault-related characteristic frequency and its harmonics can be identified through spectral analysis in the frequency domain [17]. The formulae for the various characteristic frequencies are as follows:

Ball spin frequency (BSF):

$$BSF = f_{rR} = \frac{Df_r}{2d}[1 - (\frac{d}{D}\cos\beta)^2] \tag{10}$$

Ball pass frequency, inner race (BPFI):

$$BPFI = f_{rI} = \frac{nf_r}{2}(1 + \frac{d}{D}\cos\beta) \tag{11}$$

Ball pass frequency, outer race (BPFO):

$$BPFO = f_{rO} = \frac{nf_r}{2}(1 - \frac{d}{D}\cos\beta) \tag{12}$$

Fundamental train frequency (FTF):

$$FTF = f_{rC} = \frac{f_r}{2}(1 - \frac{d}{D}\cos\beta) \tag{13}$$

Here, f_r is the rotating speed of the bearing shaft (Hz), n is the number of rolling elements, d is the mean diameter of the rolling elements (mm), D is the pitch diameter of the bearing (mm), and β is the contact angle (^{o}).

B. The Proposed Method

The function of fan bearings is to reduce friction and allow a fan to operate at high speeds with lower noise. In cases where noise can be heard, serious faults may have developed on different parts of the bearing, complicating the vibration measurement. In addition, fan bearings used in computer cooling fans are small (5–8 mm in pitch diameter), which makes it almost impossible to place several sensors on different positions around the bearings for data collection. The DWT is a quadratic sub-band filtering technique that can decompose the original signal into different bands, and the Hilbert transform provides a means of signal demodulation. Therefore, these two techniques are used in fan bearing vibration analysis for the identification of faults. A flow chart of the fan bearing fault identification method based on the wavelet and the Hilbert transforms is shown in Fig. 1.

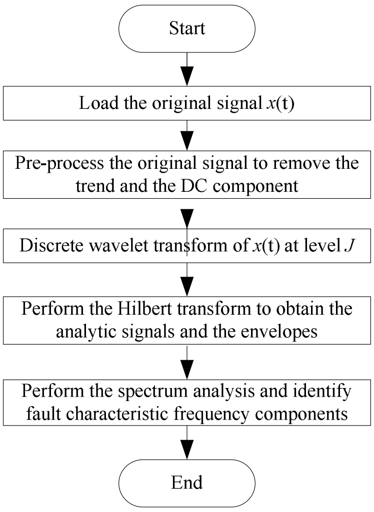

Figure 1. Flow chart of the proposed method.

Given a piece of signal $x(t)$, a pre-processing step is necessary to reduce the trend and the DC component in the signal. That is,

$$y(t) = \frac{x(t) - \bar{x}}{\sigma} \tag{14}$$

where $y(t)$ is the pre-processed signal, $\bar{x}$ is the mean value of $x(t)$, and σ is the standard deviation of $x(t)$.

In order to obtain sub-signals corresponding to different frequency bands, the DWT with the Daubechies wavelet is utilized, and the decomposition level is J. Therefore, a series of detail signals $D_j(t)$ with $j = 1,2,...,J$ can be obtained, and the frequency range of $D_j(t)$ is described in (7).

When a local fault exists in the bearing, there is modulation in the signal. To reduce the impact of modulation, the Hilbert transform was performed on all of the detail signals using (8) and (9), and the corresponding analytical signals and their envelopes, $a_j(t)$ ($j = 1,2,...,J$), can be obtained. Here, $a_j(t)$ is the envelope signal of the jth detail signal $D_j(t)$ after the Hilbert transform. To identify the existence of characteristic frequency components (such as BSF, BPFI, BPFO, FTF) of the bearing, perform the spectrum analysis of $a_j(t)$ by

$$ES_j(f) = \left| \int_{-\infty}^{+\infty} a_j(t) e^{-2\pi f t i} dt \right| \tag{15}$$

Here, $ES_j(f)$ denotes the absolute value of the Fourier transform amplitude of the jth envelope $a_j(t)$.

IV. CASE STUDY

A. Description of Experiment

The normal lifespan of a cooling fan can be several years, and it is unrealistic to conduct an experiment for such a long time. For a bearing to have its nominal lifespan at its nominal maximum load, lubrication has a critical impact on the lifespan of the bearing. Therefore, it is reasonable to accelerate the fan bearing experiment through the reduction of the lubrication level. Assuming that the nominal amount of lubricant is at the 100% level, then a certain lubrication level p% describes the percentage of lubricant being added in the bearing.

In this study, an experiment was conducted to validate the proposed method for fan bearing fault identification. To accelerate the experiment, the lubrication level was 0%, which means that no lubricant was in the bearing. Figure 2 shows the cooling fan with bearings tested in this experiment.

Figure 2. The cooling fan with bearings being tested in this experiment.

The specifications of the fan bearing in our experiment are given in Table 1. The cooling fan used in this experiment was in its brand new state with ungreased ball bearings before the experiment. At the beginning, the vibration signal of the fan was collected at a sampling frequency of 102.4 kHz with 10-second periods under an ambient environment. The fan speed was 4,000 rpm. After that, the cooling fan was stressed in a chamber at a high temperature (70^{o}C). After 72 hours of running at its maximum speed of 4800 rpm, the vibration signal of the fan was collected at a sampling frequency of 102.4 kHz with 10-second periods under an ambient environment. The fan speed was 4,000 rpm. Therefore, the rotation speed of the bearing during data collection was $f_r = 66.67$ Hz. Using (10)–(13), the various fault characteristic frequencies were determined, as listed in Table 2.

TABLE I. FAN BEARING SPECIFICATIONS

Number of rolling elements n	6
Diameter of rolling element d	1.59 mm
Pitch diameter of bearing D	5.50mm
Contact angle β	10.4°

TABLE II. CHARACTERISTIC FREQUENCIES OF FAN BEARING

Ball spin frequency (f_{rR})	211.96 Hz
Ball pass frequency, inner race (f_{rI})	256.87 Hz
Ball pass frequency, outer race (f_{rO})	143.13 Hz
Fundamental train frequency (f_{rC})	23.85 Hz

B. *Experimental Results*

To validate the proposed method, the vibration signals collected before and after the 72-hour stressing experiment were used to conduct the following analysis. The Daubechies wavelet dB10 was used for signal decomposition; the decomposition level was J =6. The Hilbert transform was applied to demodulate the details $D_j(t)$ with $j = 1,2,...,6$.

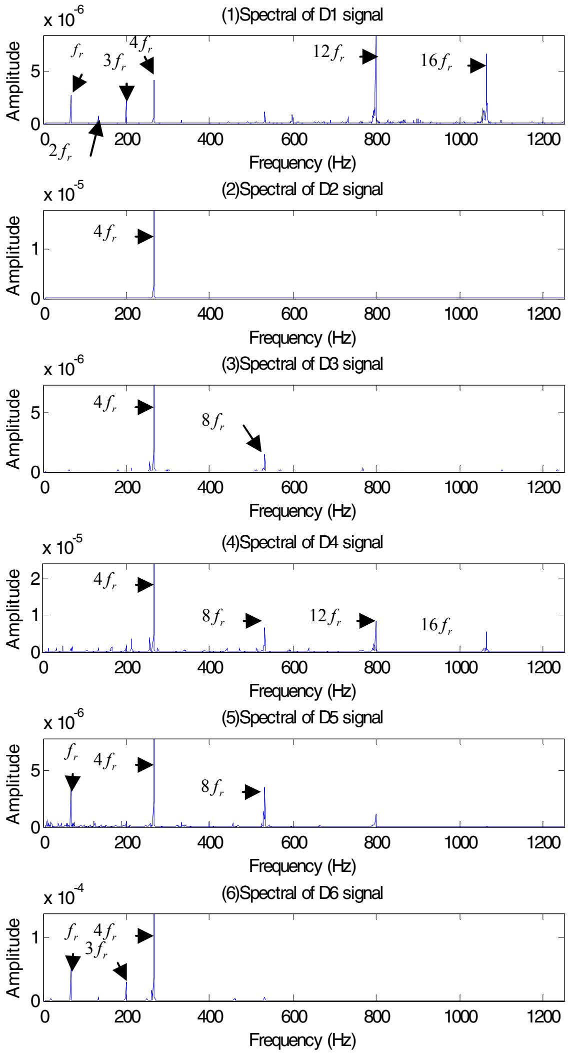

Figure 3. Analysis results of the fan bearing before the stressing experiment.

The analysis results of the fan bearing before the stressing experiment are shown in Fig. 3. Since the ball bearing was in a brand new state at the beginning, no fault-related frequency components were found from the spectra of the detail signals.

Fig. 4 shows the analysis results of the fan bearing after the 72-hour stressing experiment. From the spectra of detail signals $D_1(t),..., D_6(t)$, many fault-related characteristic frequencies and their harmonics were identified, which indicated that there were several local faults at different parts of the fan bearing. In fact, noise coming from the fan was heard at the end of the experiment.

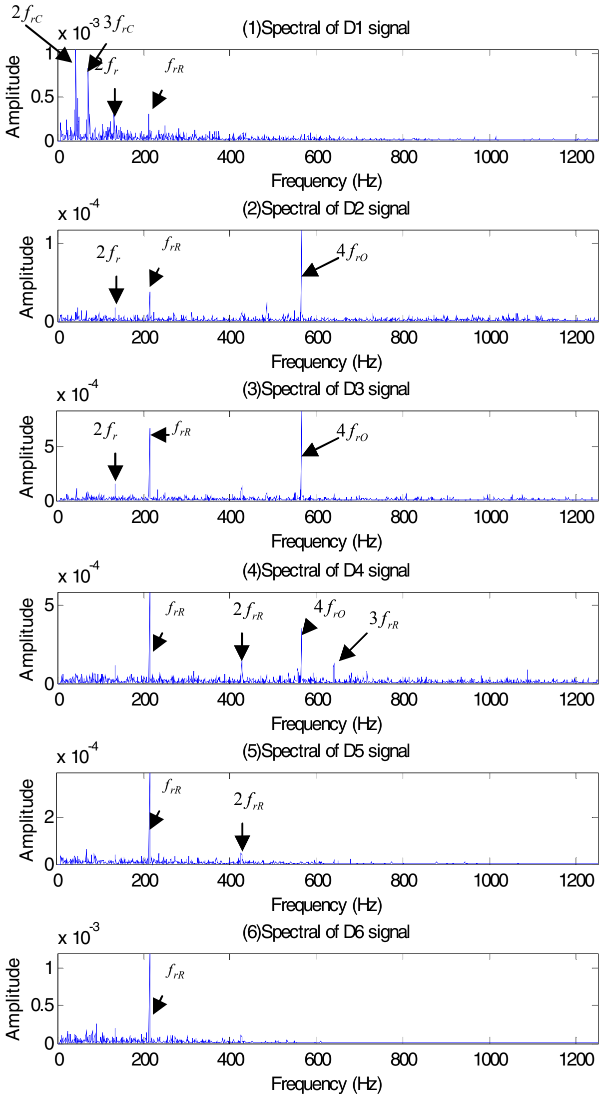

Figure 4. Analysis results of the fan bearing after 72-hour stressing experiment.

V. CONCLUSIONS

Cooling fan bearing failure is a major failure mode in computer cooling systems. Cooling fan bearing failure can result in system instability, malfunction, and damage to the computer system. In this paper, a fan bearing fault identification method based on the discrete wavelet transform and the Hilbert transform is proposed. In order to validate the proposed method, an experiment with ungreased fan bearings was conducted to obtain the vibration signal before and after failure. The analysis results showed that the proposed method can identify the fault-related characteristic frequencies of the fan bearing.

The work described in this paper provides a promising way to establish potential metrics for the description of bearing health degradation. Therefore, it is desirable to develop a condition monitoring system based on the proposed method and realize on-line health evaluation of cooling fans. With such a function, the critical failure of cooling systems can be avoided, and the reliability and availability of electronics systems can be guaranteed.

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