Fan Bearing Fault Diagnosis Based on Continuous Wavelet Transform and Autocorrelation

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Abstract—Cooling fan is commonly used in electronic system, and it is crucial for guarantying the reliability of it. In a cooling fan assembly, fan bearing failure is a major part which causes noise, vibration; reduction in rotation speed, or even locks the motor. It is necessary to conduct research on the life assessment of fan bearings. This paper presents a vibration-based fan bearing prognosis and health evaluation through continuous-wavelet transform with ACFIs. The autocorrelation function indicator (ACFI) was used for determining the coefficients of continuous-wavelet transform (CWT). A cooling fan accelerated life test was conducted to collect the lifetime vibration data of fan bearing. In addition, comparisons between the frequency spectrum of the proposed method and some commonly used methods were conducted to evaluate performance of this method. The work presented in this paper provides a promising way for finding the fault characteristic frequencies and detecting the work state of fan bearing.

Keywords- cooling fan; health assessment; continuous-wavelet transform; AutoCorrelation Function Indicator

I. INTRODUCTION

With the higher level of integration and intelligence of electronic system, energy consumption became increasing, which resulted in the raise of heat flux density and temperature in electronic devices. Keeping the cooling fan working properly can improve the reliability of electronic systems [1]. According to [2], a typical cooling fan includes shaft, bearings, fan blades and fan housing, in which bearing failure is one of the top contributors to fan failure.

As a typical rolling-element bearing, ball bearing is the fundamental rotating part in mechanical system, and a lot of research has been conducted in bearing fault diagnosis [3-7]. Pan et al. [8] proposed a hybrid model for bearing performance degradation utilizing support vector data description and fuzzy c-means. Yu [9] developed a bearing performance degradation assessment with using locality preserving projections and Gaussian mixture models. Wong et al [10] proposed a new approach combining autoregressive model and fuzzy cluster analysis for bearing diagnosis and degradation assessment. He et al. [11] presented a joint adaptive wavelet filter and morphological signal processing method for weak mechanical impulse extraction.

This paper presents a method for the cooling fan bearing fault diagnosis. The method utilizes the ACFI to choose the scale of continuous-wavelet transform (CWT) with Morlet. The spectrum obtained through this method can give a visual description of fault process and extent. A comparative study was conducted between the proposed method and some traditional methods.

II. PRINCIPLE OF CONTINUOUS WAVELET TRANSFORM AND AUTOCORRELATION FUNCTION

A. Continuous-wavelet filtering

The continuous-wavelet transform (CWT) provides a time-frequency representation of a signal through a set of wavelets which has different scale. The wavelet used in CWT is defined by different wavelet basis function [12]. It has been used widely in the area of fault diagnosis and signal processing. Given a mother wavelet function \( \psi(t) \), a series of wavelet can be defined as:

\[
\psi_{a,b}(t) = a^{-1/2} \psi \left( \frac{t-b}{a} \right), a,b \in \mathbb{R}, a \neq 0
\]

where \( a \) is the scale parameter, and \( b \) is the translation parameter.

The wavelet function \( \psi(t) \) should satisfy the relation:

\[
C_{\psi} = \int_{\mathbb{R}} \frac{|\psi(\omega)|^2}{|\omega|} d\omega < \infty
\]

where \( \psi(\omega) \) denotes the Fourier transform of \( \psi(t) \), and \( R \) represents the real number. The continuous wavelet transform of a signal \( x(t) \) can be described as:

\[
W(a,b) = \left( x(t), \psi_{a,b}(t) \right) = |a|^{-1/2} \int_{\mathbb{R}} x(t) \psi^* \left( \frac{t-b}{a} \right) dt
\]
The equivalent frequency-domain representation can be expressed as:

$$ WT(a, b) = \sqrt{a} F^{-1} \left[ X(f) \Psi'(af) \right] $$

(4)

where $X(f)$ and $\Psi(f)$ are the Fourier transform of $x(t)$ and $\psi(t)$, and $F^{-1}$ represents the inverse Fourier transform.

Accordingly, the continuous wavelet transform can be treated as a band-pass filter. The bandwidth and central frequency of the filter is determined by the scale parameter $a$ of the wavelet function.

The Morlet wavelet has been widely used in signal processing, and it can be defined as:

$$ \psi(t) = \beta e^{-a^2 t^2} e^{j2\pi f_0 t} $$

(5)

where $\sigma$ is the shape factor, $f_0$ is the central frequency of wavelet, and $\beta$ is a positive parameter.

The Fourier transform of the Morlet wavelet is:

$$ \Psi(f) = \frac{\beta \sqrt{\pi}}{\sigma} e^{\left(-\frac{f}{f_0}\right)^2} e^{j2\pi f_0 t} $$

(6)

Thus, the Morlet wavelet transform can be interpreted as a kind of filtering process, which has a central frequency of $f_0$.

B. Autocorrelation function indicator

Autocorrelation function (ACF) is widely used in signal processing and time series analysis. It reflects the correlation between the values of the different moments of the same sequence. The definitions of autocorrelation function were not completely equivalent in different areas. Given a signal $f(t)$, the continuous autocorrelation $R_g(\tau)$ is generally defined as the continuous cross-correlation integral of $f(t)$ with itself, at lag $\tau$:

$$ R_g(\tau) = f(\tau) \ast f^*(t-\tau) $$

$$ = \int_{-\infty}^{\infty} f(t+\tau) f^*(t) dt = \int_{-\infty}^{\infty} f(t) f^*(t-\tau) dt $$

(7)

where $f^*(\tau)$ represents the complex conjugate, and $\ast$ represents convolution, in which for a real function $f^* = f$.

For processes that are also ergodic, the expectation can be replaced by the limit of a time average. The autocorrelation of an ergodic process is sometimes defined as:

$$ R_{\text{g}}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} f(t+\tau) f^*(t) dt $$

(8)

The continuous autocorrelation function reaches its peak at the origin, where it takes a real value, i.e. at any lag $\tau$, $|R_{\text{g}}(\tau)| \leq R_{\text{g}}(0)$. This is a consequence of the Cauchy–Schwarz inequality. The same result holds in the discrete case. So autocorrelation function indicator can be defined as:

$$ ACFI = \frac{k}{\sum_{i=1}^{k} R_{f}(\tau)} - 1 $$

(9)

where $k$ means the size of the area which represents the correlation degree, $\max_k$ means the maximum of $k$ number of $R_f(\tau)$.

III. PROPOSED FAN BEARING HEALTH ASSESSMENT METHOD

In order to assess the effect of the proposed method, a cooling fan lifetime vibration data were used in this section. An introduction of the cooling fan life-time experiment was given firstly. The method with ACFI and CWT was introduced, and comparisons were given to validate the proposed method.

A. Description of experimental setup

The cooling fan used in this research was an axial type brushless direct current fan with the dimensions of $80 \times 80 \times 25$ mm. Two ball bearings were used in the cooling fan to support the shaft. The rotation speed of the fan was 4800rpm, corresponding to the rotation frequency $f_r$ of 80 Hz. The geometrical specifications of fan bearing were given as Table 1.

<table>
<thead>
<tr>
<th>TABLE I. THE GEOMETRICAL SPECIFICATIONS OF FAN BEARING.</th>
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<tr>
<td>Number of rolling elements $n$</td>
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<tr>
<td>Mean diameter of rolling element $d$</td>
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<tr>
<td>Pitch diameter of bearing $D$</td>
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<td>Contact angle $\gamma$</td>
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With the definitions of characteristic frequencies and the fan speed, the frequencies were given as Table 2.

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<tr>
<th>TABLE II. THE BEARING CHARACTERISTIC FREQUENCIES</th>
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<tr>
<td>Ball spin frequency (BSF)</td>
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<tr>
<td>Ball pass frequency, inner race (BPFI)</td>
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<tr>
<td>Ball pass frequency, outer race (BPFO)</td>
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In order to accelerate the experiment, the cooling fan with ungreased bearings was used, and it was placed in a chamber at a temperature of 70 °C. The test was stopped when the noise, which was collected by a microphone in this experiment, increased 3db from the initial value. This is the failure criterion defined in the IPC-9591[13] standard. The cooling fan was in its brand new state before the experiment. To measure the vibration data, a PCB 352C42 accelerometer was attached to the fan housing near the bearings. Data collection was realized with the NI LabVIEW program. The accelerated life test started at 09/09/2010 10:14, and ended at 09/22/2010 0:47. There are 387 of effective data after the experiment. The vibration signal was collected at the sampling frequency of 25.6 kHz with 10 seconds period, and the time interval between two collections was 15 minutes.

### B. Fan bearing degradation assessment

As mentioned before, each measure of different scales’ continuous-wavelet transform can be regarded as a unique filter with different center frequency and side band which was defined by the scale. So there were a series of coefficients at different scales from the same original signal after the continuous-wavelet transform with Morlet wavelet. The ACFI can help to find which scale contains the most fault-related information that can be used to find the fault feature.

For a single signal, the flowchart of the proposed fan bearing failure detection is given in Figure 1:

![Flow chart of the proposed cooling fan bearing health assessment method for single signal.](image)

In order to demonstrate the effect of Morlet wavelet transform with ACFI, an example with file number 300 is given in Figure 2. Because the fault characteristic frequencies of fan bearing were located below 800Hz, the \( k \) in ACFI set was 500 when the length of data was 1s (25600 points). The signal after CWT was shown in Figure 2(c), and it can be regard as a sub-signal of original signal.

![Single signal health assessment of each step. (a) original signal; (b) ACFIs of the signal; (c) the signal after CWT.](image)

After the processing, the periodic component of the signal was retained while the non-periodic was eliminated.

For each data file, there was a particular maximum area of ACFIs. After the same step of processing, the max scale of ACFIs was given in Figure 4:

![The maximum of ACFIs during fan bearing life.](image)

From Figure 3, obviously the maximum area of ACFIs was distributed about the scale of 40. For further analysis, all vibration signals were transformed with Fourier transform, and the results were shown in Figure 4:
In Figure 4(a), both the 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} order harmonics of rotating frequency can be recognized clearly from the beginning. In addition, the fault characteristic frequency of BSF and 2\textsuperscript{nd} order harmonics of BSF can be recognized clearly after file number 200. However, the amplitude was too small to identify the accurate time of the incipient failure. For further analysis, do natural logarithm operation on the results, and the result was shown in Figure 4(b). The fan bearing rotating frequency and its harmonics can be easily identified from the graph. The BSF and its harmonics appear between file number 50 and file number 100.

In order to make the frequency of incipient failure more prominent, zoom in Figure 4(a) as Figure 5. From Figure 5, it can be observed that the incipient failure should occur around file number 95-97, which corresponds to the time about 10.am 09/10/2010. The results of number 95 and 96 data files were extracted to present the time point of the BSF appeared in Figure 6. According to the above results on the individual data, more information about the incipient failure of cooling fan bearings can be obtained with the proposed method.

C. Comparison with other ways of bearing failure detection

In this section, a comparison study is conducted between ACFs-CWT and some other methods. In vibration analysis, DWT and Hilbert-FFT transforms are two popular methods which are used to determine the existence of fault-related characteristic frequencies. Therefore, the data of file number 96 was chosen to conduct comparisons between these methods, and the results are given in Figures 7 and 8.
IV. CONCLUSION

Cooling fan is an important part for the electronic system normal working. Identifying the beginning of failure can avoid the electronic system’s crash which may result in a more serious loss. This paper presents a solution for the health assessment of cooling fan bearing. The method utilizes the ACFI to choose the scale of CWT with Morlet wavelet. An accelerated life test on cooling fan was conducted to simulate the lubricant starvation of fan bearings. The recorded vibration data were used to validate the proposed method. To demonstrate the performance of this proposed method, a comparative study was conducted between different processing steps for vibration signals.

The work presented in this paper provides a promising way for the cooling fan bearing health evaluation and prognosis. With such a function, the critical failure of cooling system can be avoided, and the reliability of electronic systems can be guaranteed. Further, the proposed solution may also be used in the generic bearing health evaluation and prognosis, which is currently the focus of mechanical system prognostics and health management.

V. ACKNOWLEDGMENT

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