Rolling Bearing Fault Diagnosis Based on GUI System

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Abstract. Rolling bearing can be used in many complex weapon equipments to reduce friction and improve their productivity. Accordingly, a rolling bearing fault diagnosis and life prediction system interface is made by using the graphical user interface system module of MATLAB so that the theoretical value of the local defect frequency can be calculated based on the possible fault types of the main structure of the rolling bearing. Then the fault category of bearing can be identified by comparing the impact interval frequency of bearing fault extracted by Hilbert transform with the theoretical fault frequency.

1. Introduction
Most weapons and equipment adopt the rolling bearing [1]. For example, the trunnion part of the launching arm on the missile launch vehicle is rotated by rolling bearings, and many small and medium-sized motors involve in rolling bearings as well [2]. Generally speaking, rolling bearing mainly consists of four basic parts: inner ring, outer ring, rolling element and cage. According to the reference 3, the inner ring is usually the closest part to the shaft, working together with the shaft; the outer ring serves as the important base in the internal structure of the bearing and makes transition with the shaft seat; the rolling element makes rolling friction between the inner and outer rings, and its volume and number will directly affect the working performance and load capacity of the rolling bearing; the cage can not only make the rolling elements evenly distributed on the circumference, but also make them rotate [3]. These four parts tends to be the home for the main faults of rolling bearing. In this paper, Hilbert algorithm is used to determine the type of bearing fault, and by using GUI interface module to make diagnosis and to make maintenance more convenient and quicker.

2. Damage problems caused by main failure types of rolling bearing

2.1 Fatigue spalling and pitting corrosion of rolling bearing
This damage problem mainly stems from the defective inner and outer rings. This is because the rolling element on the raceway of rolling bearing bears most of load repeatedly. So it is not uncommon that the small cracks at a certain depth from the contact surface after a working span and then the small cracks may move to the contact surface, which causes the metal on the contact surface to flake off and form pits on the bearing surface. This kind of damage problem is the so-called common rolling bearing fatigue spalling and pitting corrosion.
2.2 Abrasion and graze
The abrasion and graze comes from the rolling element impacting on one side or both sides of raceway. To illustrate, when there is relative movement between the rolling element and the raceway of the rolling bearing, various pollutants such as external viscous substances and particles will join them, causing bearing abrasion and graze.

2.3 The friction or fraction of the cage
This kind of damage problem is caused by the friction between cage and inner or outer raceway. More specifically, the friction or fraction of the cage will present when the rolling bearing is not perfect, affected by external force or changes direction for many times. If there is friction between cage and inner ring or outer ring, the bearing will produce noise or vibration when it works. But when the situation becomes worse, the rolling element may be stuck seriously, powering the rolling bearing. At this stage, the friction between the two will shift from rolling friction to sliding friction. This will lead to the rapid rise of the temperature of the internal parts of the bearing, and the bearing may even be damage or burnt.

3. Calculation of rolling bearing failure frequency
As long as there is a local fault at the contact between the rolling element and the inner and outer raceway surface, an impact vibration signal will appear apparently. When the contact points of the two surfaces pass through different bearing elements, there will be different partial failure. The frequency of their shock vibration signals is quite different, which is called the impact interval frequency or fault characteristic frequency. The value of the fault interval frequency is related to the motion relationship of the bearing, the shape of each component and the rotational speed, so the combination of these several factors can lead to the outcome of the frequency value.

The inner ring, router ring of rolling element and cage are the main parts of rolling bearing. The partial failures within these parts can be divided into three types.

The inner and outer ring defects are the first kind of fault, the rolling element defect and the cage failure belongs to the second and third type fault respectively. The speed relationship of the bearing is shown in Fig. 1[4], and the sectional view of the bearing geometry dimension is shown in Fig. 2[5].

Since the outer ring raceway of the common rolling bearing is always stationary, the inner ring raceway keeps rotating and the speed rate is known to be \( n_i \). Assuming that the cage speed is \( n_c \), the inner ring raceway speed is \( n_w \) (relative to the cage), and the rolling body's rotation speed is \( n_e \), according to reference 6, it can be known that:

\[
n_e = \frac{n_i}{2} \left(1 - \frac{d \cos \alpha}{D} \right) \tag{1}
\]

\[
n_w = n_i - n_e = \frac{n_i}{2} \left(1 + \frac{d \cos \alpha}{D} \right) \tag{2}
\]

\[
n_s = \frac{D}{d} (n_i - n_c)
\]

\[
= \frac{D}{2d} n_i (1 - \frac{d \cos \alpha}{D})(1 + \frac{d \cos \alpha}{D}) \tag{3}
\]
In this formula, the \(D_c\) serves as the diameter of the middle circle of the rolling element (mm), while \(d\) acts as the diameter of rolling element and \(\alpha\) is the angle between the contact point in the axial plane and the center line of the rolling element (rad or \(^\circ\)). These three faults can be transformed into the form of frequency.

These three kinds of failures can be transformed into the form of vibration interval frequency. The first type: it refers to the failure frequency when there is a fault in the inner ring raceway:

\[
f_0 = \frac{n_i z}{120} \left(1 + \frac{d}{D_n} \cos \alpha \right) \quad (4)
\]

It also refers to the failure frequency when there is a fault in the outer ring raceway:

\[
f_1 = \frac{n_i z}{120} \left(1 - \frac{d}{D_n} \cos \alpha \right) \quad (5)
\]

The second type: it refers to the impact interval frequency when the rolling element is in front of one side raceway:

\[
f_{d1} = \frac{n_i D_m}{120d} \left(1 - \frac{d^2 \cos^2 \alpha}{D_n^2} \right) \quad (6)
\]

It also refers to the impact interval frequency when the rolling element is in front of both sides of raceway:

\[
f_{d2} = \frac{n_i D_m}{60d} \left(1 - \frac{d^2 \cos^2 \alpha}{D_n^2} \right) \quad (7)
\]

The third type: it refers to the impact interval frequency when there is a friction between the cage and the outer ring:

\[
f_{ec} = \frac{n_i}{120} \left(1 - \frac{d}{D_n} \cos \alpha \right) \quad (8)
\]

It also refers to the impact interval frequency when there is a friction between the cage and the inner ring:

\[
f_{ic} = \frac{n_i}{120} \left(1 + \frac{d}{D_n} \cos \alpha \right) \quad (9)
\]

4. System algorithm principle

4.1. Hilbert transform principle

Hilbert transform is an important algorithm tool used by experts in signal analysis. In most cases, the Hilbert transform is used to demodulate the signal [6]. The essence of signal processing with Hilbert algorithm described in references 7 and 8, refers to a real measurable signal transformed into a complex signal with real and imaginary parts, also called the analytical signal. The purpose of this transformation is to obtain the instantaneous phase and frequency of the real signal conveniently. It is
supposed that the continuous signal is $x(t)$ within the certain time, and $x(t) = a(t) \cos(2\pi f_c t)$, then the convolution of $x(t)$ and $\frac{1}{\pi t}$ is the Hilbert transform of $x(t)$.

$$\hat{x}(t) = x(t) * \frac{1}{\pi t}$$

$$F^T(\frac{1}{\pi t}) = -j\text{sgn}(\omega) \hat{F}(j\omega)$$

$$= X(j\omega)H(j\omega)$$

$$= \begin{cases}  
-jX(j\omega) & \omega > 0 \\
  jX(j\omega) & \omega < 0 
\end{cases}$$

$$\hat{x}(t) = a(t) \sin(2\pi f_c t)$$

The reference 7 demonstrates that FFT algorithm transformation is carried out on $\hat{x}(t)$, that is, the phase of continuous signal is shifted in the frequency domain. If the frequency domain of the signal is positive, the signal is shifted backward by $\frac{\pi}{2}$; if not, it is shifted forward by $\frac{\pi}{2}$.

Then the extracted analytic signal is $s(t)$, and there is

$$s(t) = x(t) + j\hat{x}(t)$$

It is shown in reference 8 and 9 that the amplitude of the signal is and then the power spectrum of the amplitude $x$ is drawn. Then the frequency value to be extracted is the maximum amplitude in the figure. Next the theoretical frequency value of the corresponding fault type can be obtained according to equations (4) to (9) and finally we can identify the failure type of the rolling bearing by comparison.

5. GUI system simulation

5.1 Simulation idea

The GUI module is used in the design of the main interface which consist of three modules: the first module is to calculate the theoretical value of rolling bearing defect frequency, including the theoretical value calculation module of inner and outer ring defect frequency, the rolling element impact unilateral raceway and the cage and outer ring friction; The second module is to extract the failure interval frequency module, including the time domain waveform diagram module of the experimental data signal, the power spectrum diagram module of the experimental data signal and the fault impulse interval frequency module after Hilbert transformation; the third module is to identify the failure type of the rolling bearing.

After typing the rotational speed, number of rolling elements, diameter of rolling element, pitch diameter of raceway and contact angle of the bearing, the theoretical value of defect frequency of inner and outer ring in the module, the theoretical value of defect frequency of rolling element and cage can be calculated. Then the impact interval frequency of bearing fault is extracted by Hilbert transform. The failure type of rolling bearing can be identified by judging which theoretical value the impact interval frequency is closest to.

5.2 Simulation result

The bearing failure data originates from the drive end acceleration (DE) in 290. mat of CWRU [18]. The theoretical values of local fault frequency can be obtained by inputting various theoretical parameters of the rolling bearing, and the parameters are as shown in Table 1. More specifically, the theoretical values of six local fault frequencies can be calculated based on the assumption where there is no motor load, as shown in Fig 3.
Table 1. The theoretical value of the defect frequency

| Speed r/min | Rolling element number | Roll diameter d/mm | Pitch diameter Dm/mm | Contact angle α/°rad | Sampling frequency fs/HZ |
|------------|-----------------------|-------------------|---------------------|----------------------|------------------------|
| 1796       | 10                    | 0.294             | 2.034               | 0                    | 12000                  |

The results showed that the theoretical value of inner ring and outer ring defect frequency is 171.299HZ and 128.0334HZ respectively; the theoretical value of roller bearing impact single measurement raceway frequency is 101.3816HZ, while the figure in raceway frequency on both sides of impact is 202.7631HZ, the theoretical value of friction between cage and bearing outer ring is 12.8033HZ, and the theoretical value of friction between cage and bearing inner ring is 17.1299HZ.

Next, click the second large module on the main interface, and respectively click the vibration signal time domain waveform diagram, vibration signal power spectrum diagram and fault interval frequency extraction to get the following results, as shown in Figure 4.

It is found that the frequency of the maximum amplitude in the power spectrum is 2989HZ based on the operation results of the system, but its location is not proper in terms of the fault interval frequency. If we directly analyze the frequency spectrum, we cannot accurately measure the fault interval frequency value we want. So the frequency of the original shock signal is known to be 134.498HZ after being transformed by Hilbert algorithm.

Finally, click the big module of identifying bearing fault type in the main interface to get the final diagnosis result of the system, as shown in Fig. 5.

It is found that the extracted fault interval frequency is 134.498HZ, which is closest to the theoretical value of 128.0334HZ of outer ring defect frequency. Therefore, the early fault type obtained from this data is viewed as the outer ring fault of rolling bearing. Then the system is tested with other data of CWRU, and it is found that the system has performance with high accuracy.
Figure.4 Vibration signal time domain waveform diagram, power spectrum figure

Figure.5 The conclusion of diagnosis

6. Conclusion
In this paper, a failure diagnosis and the prediction system for remaining working time of rolling bearing is designed by using the GUI design module of MATLAB software. In addition, the CWRU data was used to verify the feasibility of Hilbert transform algorithm to extract the fault interval frequency of rolling bearing, and finally the failure type of the rolling bearing.

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