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RESEARCH ARTICLE

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HHT-based crack identification method for start-up rotor

Abstract This paper presents a crack identification method for start-up rotor based on the Hilbert-Huang transform (HHT). With this method, the instantaneous frequency (IF) of each intrinsic mode function is obtained through the Hilbert transform, and the spectrum of IF is calculated accordingly. The influence of acceleration and crack depth on the rotor is analyzed through experiments. HHT is employed to detect the shallower crack, and is then tested during the start-up process of the rotor. The results of the experiment show that HHT is a better tool for crack detection than fast Fourier transform.

Keywords cracked rotor, start-up, Hilbert-Huang transform (HHT)

1 Introduction

With the improvements in modern industry and in technology, rotating machinery has taken on an increasingly important role in many fields, such as energy, transportation, the chemical and auto industry, and so on. The operating speed, power, and load of a rotating machinery increases if its weight and dimensional tolerance decrease for operations at higher mechanical efficiency. Consequently, many practical rotor dynamic systems containing rotor elements are highly susceptible to transverse cracks because of fatigue. A crack not detected in time can result in catastrophic failure, and cause injuries and severe damage to machinery. Therefore, the study of the dynamics of a faulty rotor and crack detection is receiving increasing recognition [1–3].

Pennacchi et al. [4] used fast Fourier transform (FFT) and a model-based method to identify the cracks not only in a slotted rotor, but also in the breathing type and in a relatively large experimental rig. FFT reveals the spectral content of a signal, but gives no information regarding when those spectral components appear. One has to assume that the data analysis is stationary [5]. The Hilbert-Huang transform (HHT) is an efficient method for analyzing nonlinear and non-stationary data [6]. The method was developed by Norden E. Huang of the National Aeronautics and Space Administration. The HHT is currently used in the fields of physical geography [7], signal processing [8], fault diagnosis [5], etc. Recently, HHT, which is potentially viable for nonlinear and non-stationary data analysis especially for time-frequency-energy representations, has been evaluated for its potential application in crack detection [9].

In this paper, the influence of acceleration and crack depth on the rotor was analyzed through experiments. The novel and advanced HHT was employed to detect shallower cracks and was tested in the start-up experiment. The results of the experiment showed that HHT is a better tool for crack detection than FFT.

2 Basic theory of HHT

The key component of HHT is the empirical mode decomposition method, with which any complicated data set may be decomposed into a finite, and often small, number of intrinsic mode functions (IMFs) $c_i(t)$ $(i = 1,2,\ldots,n)$ and a remainder r_n, which are shown as [6,10]

$$s(t) = \sum_{i=1}^{n} c_i(t) + r_n(t). \tag{1}$$

The gained IMFs $c_i(t)$ then admit well-behaved Hilbert transforms. With the Hilbert transform, the IMFs yield instantaneous frequencies (IFs) as functions of time that give sharp identifications of imbedded structures.

For an arbitrary time series $s(t)$, we can always have its Hilbert transform $y(t)$ as follows:

$$y(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{s(\tau)}{t-\tau}\mathrm{d}\tau. \tag{2}$$

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With this definition, $s(t)$ and $y(t)$ form the complex conjugate pair. Thus, we obtain an analytic signal $z(t)$ as

$$z(t) = s(t) + iy(t) = a(t)\mathrm{e}^{\mathrm{i}\Phi(t)}, \tag{3}$$

in which

$$a(t) = [s^2(t) + y^2(t)]^{\frac{1}{2}},$$

$$\Phi(t) = \arctan\frac{y(t)}{s(t)}. \tag{4}$$

The IF $f(t)$ can be obtained as

$$f(t) = \frac{1}{2\pi}\frac{\mathrm{d}\Phi(t)}{\mathrm{d}t}. \tag{5}$$

Nonlinear and non-stationary data widely exist in the large, complicated electromechanical rotor system. In this paper, the vibration signal from the cracked rotor has a non-stationary characteristic. Thus, the proposed crack identification method based on HHT is used in the signal analysis, and the crack for the start-up rotor is successfully diagnosed.

3 Experiments

3.1 Experiment set

In this paper, the harmonic resonance of the cracked rotor system with a single disk was studied and tested using the Bently rotor test rig. The equipment used in the experiment included a rotor test rig, an AC variable speed control device, eddy current sensors, and a data acquisition system. The rotor test rig included the base, bearing seats, cracked shaft with the same diameter, and the rigid disc, as shown in Fig. 1. The bearing seats could be moved anywhere on the guide rail of the base; thus, the span of the support and the location of the crack in relation to the bearing seat could be controlled. One end of the shaft was connected to the AC variable speed motor, the speed of which was controlled by the AC variable speed control device.

Three eddy current sensors were used in the experiment to measure the key-phase signal, the horizontal displacement x, and the vertical displacement y. For the rotary machine, the absolute displacement could be measured conveniently using non-contact eddy current sensors. A couple of vertical and horizontal eddy current sensors were installed in the sensor supporting bracket near the rigid disc to measure the motion trail at the geometric center of the shaft.

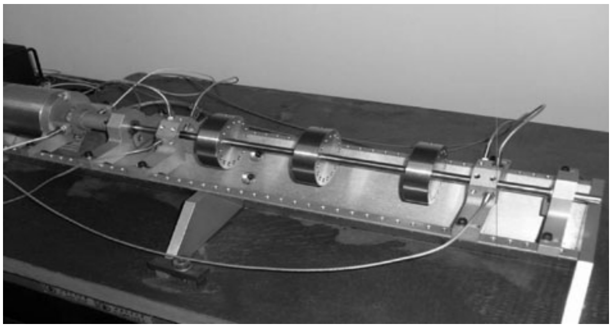


Fig. 1 Bently rotor test rig

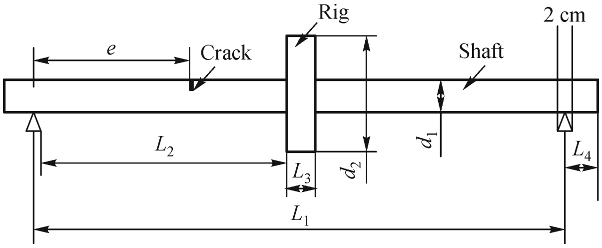


Fig. 2 Reduced graph of Bently rotor test rig

The sampling frequency was 1024 Hz, and the data length was determined by the acceleration. The brief graph of the Bently rotor test rig is shown in Fig. 2, and the geometric parameters are shown in Table 1. The collected data were analyzed by signal processing methods such as FFT, and by HHT to extract the fault characteristics; the results were then compared.

With the increases in time, a variety of the frequency during the start-up process was observed using the SONY-EX system, and the first critical speed was 2400 r/min. Too many run times would cause plastic deformation in the cracked shaft, and would bring about end of life. In addition, the rotor vibration of the deep crack increases at a high speed. Hence, one group of experiments for the start-up process was conducted under each condition, and the speed was increased from 0 to 6000 r/min.

The shafts in the experiment included a non-destructive shaft and a cracked one (crack depth a was 2 mm, $a/d_1 = 0.2$). The crack in the rotor was obtained through the cutter. The width of the crack was less than 0.2 mm.

3.2 Experimental results

The transient vibration signals of the cracked and the crack-free rotor under moderate acceleration (Fig. 3) were

Table 1 Geometric parameters of Bently rotor test (rig/mm)

Parameter	L_1	L_2	L_3	e	L_4	d_1	d_2
Value	478	226	26	60	30	10	75

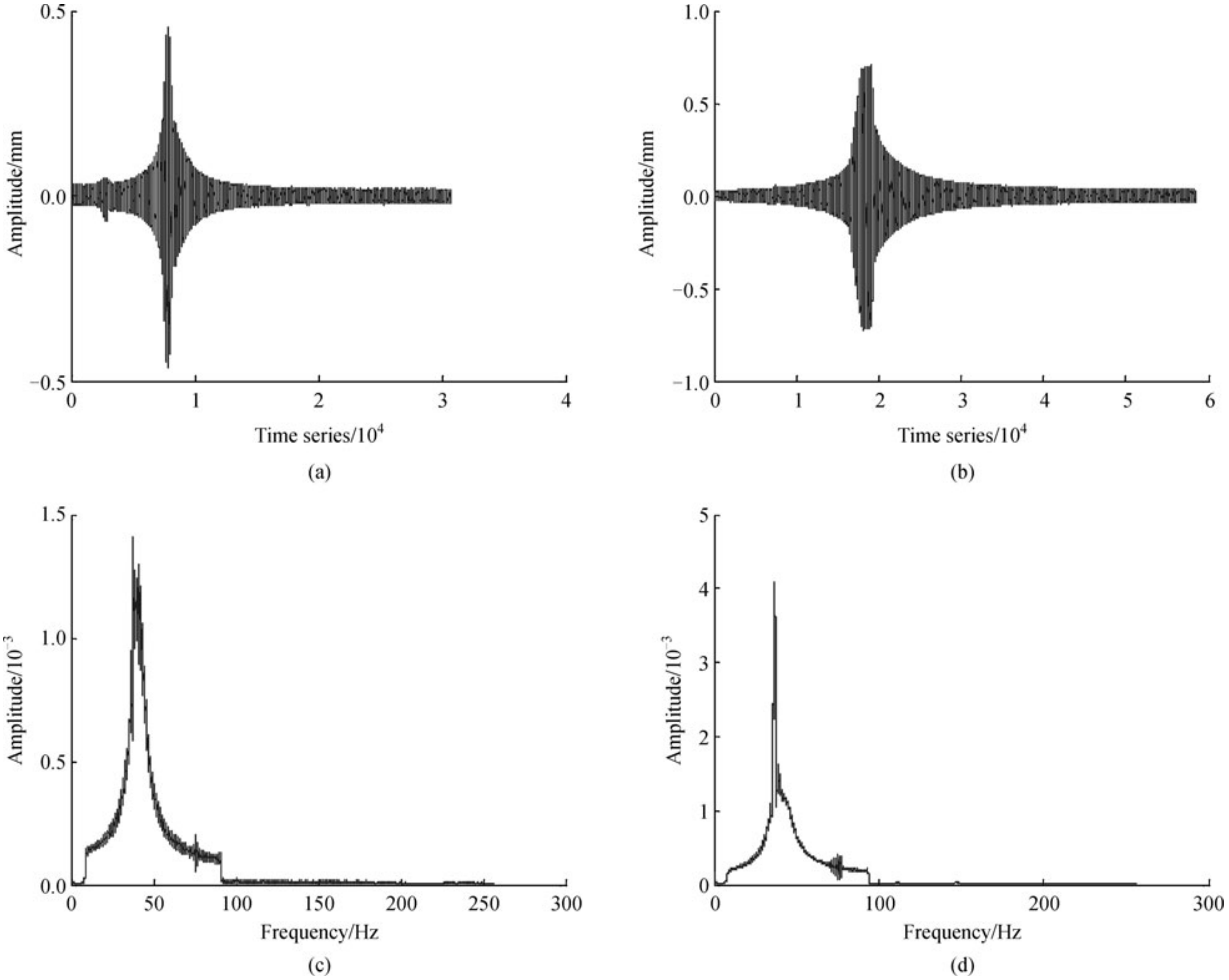


Fig. 3 Time and frequency domain response of crack-free and cracked rotor. (a) Vibration signal of crack-free rotor; (b) vibration signal of cracked rotor; (c) FFT of crack-free rotor; (d) FFT of cracked rotor

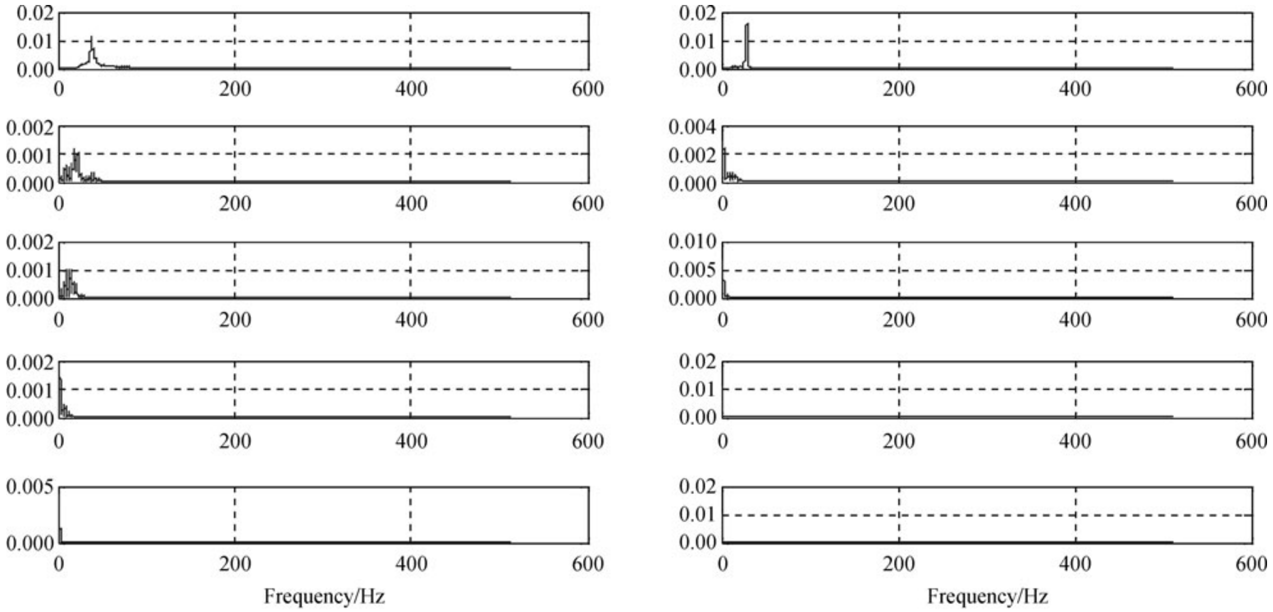
analyzed by HHT. The spectrum graph of each intrinsic mode component and the time-frequency characteristic of the vibration signals are shown in Fig. 4.

The subharmonic resonance of the cracked rotor observed in the progress of the start-up may be used for crack identification, but it could hardly be identified especially when the acceleration was high or the crack was weak. The harmonic component was also difficult to discern via normal frequency analysis methods such as the FFT, as both the duration of the harmonic component was short and the vibration signal was transient. Figure 5 shows that the harmonic component was clearly observed in the Hilbert time-frequency characteristic by the HHT method.

Tphe colour depth in Fig. 5 represents the magnitude of the frequency. By ignoring the small perturbations of frequency caused by the introduced noise, the time-frequency characteristic graph easily shows that the frequency of the crack-free vibration signal increases linearly with time, which corresponds to the constant acceleration process of the crack-free rotor. The cracked rotor generates frequency disorders at the 3500 time series, and the high frequency is easily detected, corresponding to the harmonic resonance of the cracked rotor in the time domain. The test results indicate that the HHT method is very effective for non-stationary transient signals because it can reveal the time-frequency features of the vibration signal, and it can diagnose the early faults of the rotor system.

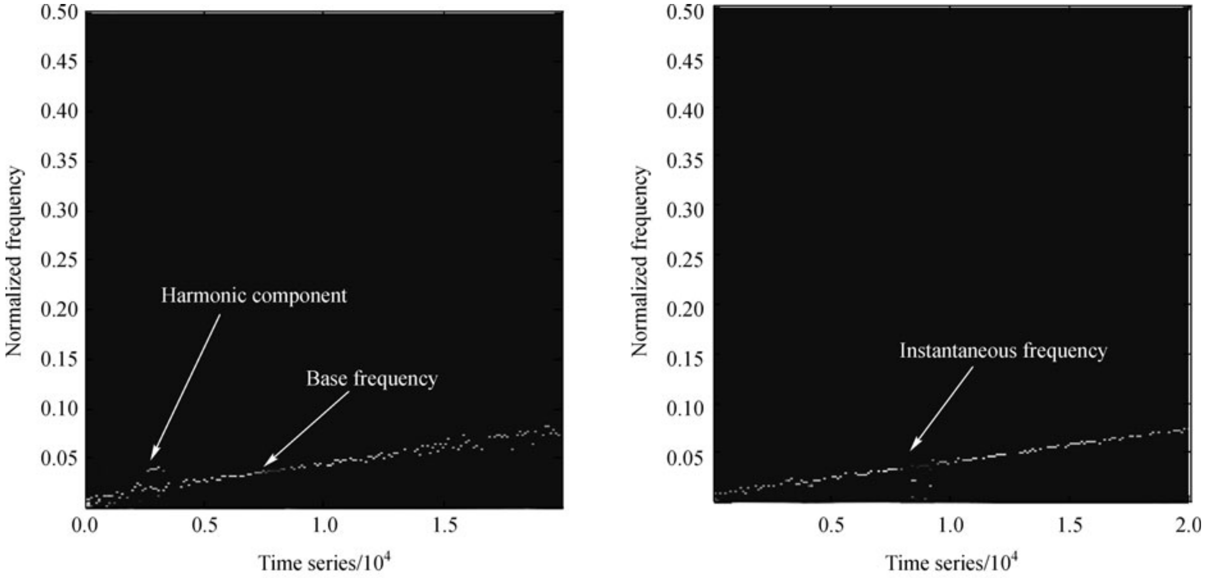
4 Conclusions

This paper presents a fault diagnosis method based on the HHT. The method is applied to crack fault diagnosis for rotors in rotating machinery. The time-frequency analysis techniques based on the HHT could express the concept of IF and detect the weak exotic ingredients of the signal. Moreover, the techniques could effectively extract the high



(a) (b)

Fig. 4 Spectrum graph of each intrinsic mode component of vibration signals. (a) Intrinsic mode component of crack-free rotor; (b) intrinsic mode component of cracked rotor



(a) (b)

Fig. 5 Hilbert time-frequency characteristic of vibration signals. (a) Crack-free rotor; (b) cracked rotor

frequency components of the rotor system caused by small cracks, making it an effective tool for diagnosing the early faults of a rotor system.

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