Robust IFE Based Order Analysis of Rotating Machinery in Virtual Instrument

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Abstract. Character analysis plays an important role in fault-find and diagnosis of rotating machinery. Order analysis is one of the major methods in character analysis for the analysis of non-stationary vibration signals in run-up or coast down of rotating machinery. An order analysis method, which employs instantaneous frequency estimation based on time-frequency analysis, is introduced. In contrast with traditional order analysis methods, this method avoids the use of tachometer and other special hardware; hence it makes the application of order analysis simplified. The order analysis introduced in the paper with the character that only software is depended for order tracking makes it specially satisfy the requirement of Virtual Instruments. Corresponding order analysis items, such as order spectrum, order spectrum matrix and tracking order spectrum etc., which are applied in Virtual Instruments, are also introduced. A test example is provided to demonstrate the validity of the method presented.

1. Introduction
Nowadays fault diagnosis of rotating machinery is focused on the conditions of run-up or coast down. Among many methods which used in the application of fault diagnosis, order analysis is a kernel technique for the analysis of non-stationary vibration signals in run-up or coast down of rotating machinery. A new method for performing order analysis is introduced in this paper. It simplified the application of order analysis, and makes a strong supplement to traditional methods.

Compared with traditional methods, it avoids the use of specific tachometer and the sampling in angle domain completely, there are no keyphasor devices required by this method. Special algorithms to process original sampling data are used to perform speed tracking and sampling in angle domain.

2. Order tracking
Vibration signals of rotating machinery during run-up or coast down are non-stationary signals. So, direct spectrum analysis to these kinds of signals will lead to so-called ‘spectral smearing’ [1]. To solve this problem, angular sampling theorem and order analysis method are emerged. These kinds of non-stationary signals in time domains are turned to be stationary signals in angle domains by means of equiangular sampling for reference shaft speed. Applying conventional spectrum analysis to these stationary signals in angle domain, clear spectrum can be attained, which is called order spectrum. In the order spectrum, each line represents an order component including frequency of times of reference speed and corresponding amplitude as well.
2.1. Traditional methods
There are two traditional order tracking methods i.e. the hardware based order tracking and the computed order tracking (COT) [2,3]. However, in the two methods a keyphasor device is a must for speed tracking, which makes the order analysis more complex. In the situation where the keyphasor equipment’s installation is impossible, both methods will be failed in application.

2.2. Order tracking based on IFE
Recently, a new method of order tracking of rotating machinery based on time-frequency analysis and instantaneous frequency estimation (IFE) is proposed [4]. Here, a brief review is introduced.

Theoretically, this method makes use of the physical relation between \( n_i(t) \), the instantaneous speed of the reference shaft, and its corresponding \( f_i(t) \), instantaneous frequency, obviously

\[
 n_i(t) = 60 \times f_i(t)
\]

Where the suffix \( i \) stands for instantaneous. So, if \( f_i(t) \) is attained, the speed tracking is done.

In engineering application the vibration signals generally are multi-component signals. To multi-component signals, the peak search of TFD is more effective to get the IFE of each component signal [5]. In this paper, the peak search is employed to attain the IFE of reference shaft speed in the spectrogram of time-frequency distribution of vibration signal, and fulfills the order tracking.

In our research short-time Fourier transform (STFT) is employed and expressed by

\[
 STFT_x(\gamma)(t, f) = \int_{-\infty}^{\infty} x(\tau) \gamma^*(\tau - t) e^{-j2\pi ft} \, dt
\]

Where the asterisk stands for complex conjugate; \( \gamma(\tau) \) is a short time window, viz. the Fourier Transform of the product of signal \( x(\tau) \) and a ‘analysis window’ \( \gamma(\tau-t) \) which is centered at \( t \). And the corresponding spectrogram is given by

\[
 SPEC(t, f) = |STFT(t, f)|^2
\]

The corresponding discrete representations of equation (3) and equation (4) are

\[
 STFT(n, k) = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} x(i) \gamma^*(i - n) e^{-j2\pi ik/n}
\]

\[
 SPEC(n, k) = |STFT(n, k)|^2
\]

Where \( N \) is the length of FFT; \( n, k \) are the ‘nodes’ in the time frequency grid of the spectrum respectively. In practice, Fast Fourier Transform (FFT) is taken in the calculation by equation (4).

When the spectrogram is attained, the order tracking can be done through IFE. The main steps are:

- Pick some points along a prominent order component in the spectrogram, and use cubic spline data interpolation to obtain initial discrete search starting points \( SPEC(n, k_n), n \in (0, N - 1) \), in which every frequency bin \( k_n \) is employed as a peak search starting point at time slot \( n \).
- By peak search, to get the discrete instantaneous frequency \( f_i(n, k) \) of the reference shaft speed. The algorithm of peak search is given by:

\[
 f_i(n, k) = \arg \max \{SPEC(n, k)\}, \quad k_n - p \leq k \leq k_n + p, \quad n \in (0, N - 1)
\]

Where the notion, arg max, represents the argument (here is \( k \)) of the maximum; \( n, k \) are the time slots and frequency bins on the time-frequency plane respectively; \( p \) is the search range.

- Interpolation is employed to do the sampling in angle domain.
IFE-based order tracing method avoids the need of special hardware and leads to simplify the installation. Only the time-frequency analysis on original vibration signal, such as STFT, is required for order tracking. The older version of IFE-based order tracking is described in reference [4], and an improvement is the first step, which makes the peak search little affected by noise or other non-order components. In section 4, a test example was given to show how to do these steps in an actual test.

3. Order analysis in Virtual Instrument

Virtual Instrument is a new member of instruments family with a strong vitality. Comparing Virtual Instrument with traditional instrument, it is able to carry out some test tasks with high quality at low costs. So, with the quickly development of computer technology, it is more and more popular in many application fields. As we known, the core of VI is software. The IFE based order tracking discussed above with the character that only software depended for order tracking makes it specially satisfy the requirement of Virtual Instruments. So corresponding order analysis functions based on Virtual Instrument, which include: order amplitude (or power) spectrum, three-dimensional order spectral map and tracking order spectrum, are being programmed and introduced as follows.

3.1. Order spectrum

The proceeding to attain the order spectrum is similar to that of conventional method used for attaining frequency spectrum, i.e., using the FFT algorithm except the data for calculation are angular sampling data. So a line in order spectrum represents the ratio of the frequency to the fundamental shaft speed or so called ‘order’. Order amplitude spectrum and order power spectrum are two kinds of basic order spectrum expressed by

\[ A(l) = \frac{2}{N} \left| \sum_{n=0}^{N-1} x(n) e^{-j2\pi \frac{n}{N}} \right| \]  

Equation (7) is called the ‘order amplitude spectrum’ and the square of \( A(l) \) is called the ‘order power spectrum’. Where \( N \) is the length of data, for using FFT, usually which is chosen as the \( n \)th power of two in practice; \( x(n) \) is discrete angular sampling series; \( X(l) \) is order series.

3.2. Three-dimensional order spectrum map

Three-dimension order spectral map are composed by order, speed and amplitude of order spectrum. Except using angular sampling data, the proceeding to obtain three-dimensional order spectral map is alike to that of waterfall plot. The computing formulas are

\[ G_m(l) = \frac{4}{N^2} \left| \sum_{n=0}^{N-1} x(m, n) e^{-j2\pi \frac{n}{N}} \right|^2 \]  

\( m = 1, 2, \cdots M \)

Where \( N \) is the length of each data section; \( x(m, n) \) is the angular series of section \( m \).

With speed tracking and angular sampling, the non-stationary vibration signals of run-up or coast down in time domain turns to stationary in angle domain, therefore the stationary required for Discrete Fourier Transform is satisfactory. So, in contrast to waterfall plots, three-dimensional order spectral maps show the vibration’s features of rotating machinery more precisely.

3.3. Tracking order spectrum

Tracking order spectrum represents the variance of the selected order component with the changing of shaft speed to one. From which, the changing feature of vibration related to reference speed is showed. It is a two-dimensional plot within the horizontal axis and vertical axis of reference shaft speed and the amplitude of one selected order spectrum. In fact, tracking order spectrum is a section plane perpendicular to three-dimensional order spectrum map at one selected order along the axis of speed. The related formula are expressed by
3.4. IFE based order analysis

In realization, the previous order analyses are different from traditional methods. The IFE based order tracking is employed to provide the pseudo speed signal and to carry out further order tracking and resampling in angular domain via analyzing of the vibration signal. This method reduced greatly the needful special hardware for conventional order analysis. Thus the implementation of order analysis is simplified, and the order analysis is easier than ever.

4. Test example

Some tests are done and the results showed that the IFE based order analysis is good at performance. Here a test example is described as follows.

A test rig of rotor is showed in figure 1. The rotor was driven by a DC motor which can rotate at a speed proportion to its input voltage. In this test the input voltage is 110V and the corresponding rotating speed was about 6800 rpm. The signal of acceleration of a bearing support of the rotor was sampled during its coast down, and analyzing of the vibration signal of the rotor was fulfilled by the IFE based order analysis. The B&K accelerometer type 4370 and B&K charge amplifier type 2635 are used in this test. The data analysis parameters selected in the test were: sampling rate 40,000 Hz; length of sampling data $1258\times1024$ points; STFT by FFT length 1024 points and window (rectangle window) length 512 points with a window overlapping 384 points.

The spectrogram of the signal under down-sampling rate 16, which means the sampling rate was changed to $40,000\text{Hz} / 16=2,500\text{Hz}$ in data analysis, is shown as figure 2, which showed the time-frequency spectrogram and discovered the order components in coast down. The horizontal axis represents time $t$ in seconds while vertical axis denotes frequency $f$ scaled by Hz. And the second order component is suitable for doing peak search. By obtaining a more accurate IFE of rotating speed, a down-sampling rate 64 is applied, which means the sampling rate was changed to $40,000\text{Hz} / 64=625\text{Hz}$ in data analysis, and the corresponding spectrogram is shown as figure 3 and figure 4. The horizontal axis represents time $t$ in seconds while vertical axis denotes frequency $f$ scaled by Hz.

According to the order tracking steps mentioned in section 2, the first step is to pick some points along the second order component in the spectrogram, and use cubic spline data interpolation to obtain initial discrete search starting points, which are the dark ‘line’, discrete points, along the second order component are shown in figure3. The second step is doing the peak search, and the white points shown in figure 4 are the search result, whose time and frequency coordinates indicate the IFE of the second order component.
4.1. Pseudo-speed signal
As shown in figure 3, the second order component, confirmed by the fastest speed of reference shaft i.e., is more prominent (the darker the color, the higher the amplitude). So, it is selected to obtain the IFE by peak search

\[ f_i^q(t) = \frac{f_i^q(t)}{q} \]  

(10)

Where \( f_i^q(t) \) is the instantaneous frequency of component order \( q \), \( q \) is the selected order of signal components for doing peak search; In this example, \( q=2 \); If \( q=1 \), \( f_i^1(t) \) represents the instantaneous frequency of reference shaft.

4.2. Order spectrum
Based pseudo-speed, the interpolation was applied to treat original sampling data, and re-sampling is made in angle domain, to obtain 1024 points data, the angular sampling series. Equation (7) was employed to calculate the order power spectrum under 6000 rpm as shown in figure 5. The horizontal axis represents orders, \( l \), while vertical axis denotes the amplitude of power scaled by the square of acceleration of gravity. The order components of signal are exposed clearly.

4.3. Three-dimensional order spectrum map
Follow the steps introduced above the three-dimensional order spectrum map was attained based on pseudo-speed tracking. Note, here a strong artificial noise was added to the original acceleration signal with constant frequency 150 Hz and amplitude 0.1 scaled by acceleration of gravity. The result is shown in figure 6. The horizontal axis represents orders, \( l \), while vertical axis denotes rotating speed \( n \) scaled by rpm and the height axis is the amplitude of power scaled by the square of acceleration of gravity. The resampling start trigger speed was set to 2400 rpm. It can represent the variable components amplitude changing with the speed. The order components and non-order components of

![Figure 3. Cubic spline data interpolation result (down-sampling rate 64).](image)

![Figure 4. Peak search result (down-sampling rate 64).](image)

![Figure 5. Order spectrum.](image)

![Figure 6. Three-dimensional order spectrum map.](image)
signal are clearly shown in figure 6, in which the peaks were gathered in a narrow range which makes it more suitable for the quantitative analysis on faults diagnosis than conventional water plot.

4.4. Tracking order spectrum

The tracking order spectrum analysis is done by the method introduced above, and order 2, order 4 and order 6 components are selected. Trigger speed was set to 2400 rpm and the plot is shown as figure 7, where the horizontal axis represents rotating speed $n$ scaled by $rpm$, while vertical axis denotes the amplitude of power scaled by the square of acceleration of gravity. The variable amplitudes of selected order components changes with the varying of reference shaft speed are clearly exposed.

5. Conclusion

Theoretical analysis and actual test results indicate that the IFE based order analysis, which proposed in this paper, is feasible in application. It is an effective supplement to traditional methods on order tracking. The order tracking and equiangular sampling in the method is only by algorithm. So, the hardware such as tachometer and keyphasor device etc. is simplified. This method with the character that only software depended for order tracking makes it specially satisfy the requirement of Virtual Instruments. So its application based on Virtual Instrument has a good prospect in engineering.

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