A Signal Processing Method for Extracting Shaft Speed Information from Vibration Signal

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Abstract—**In the case of no shaft speed measurement, the effective acquisition of shaft speed information is the premise of speed-related fault feature extraction, so it is necessary to preprocess the vibration signal and extract the shaft speed information from the vibration signal. In this paper, a signal preprocessing method for extracting shaft velocity information from vibration signals is described in detail. Based on the theory of signal processing, this paper summarizes the method of extracting shaft velocity signal without shaft speed measurement, and verifies the effectiveness of relevant theoretical methods and shaft speed extraction accuracy based on practical application cases.**

Keyword: signal processing; lack of axle speed; synchronous analysis; vibration signal

I. INTRODUCTION

Similar to the traditional fault detection of rotating machinery, the most reliable in the fault detection method in the fault detection of engine transmission chain is the analysis in the periodic domain and the corresponding shaft order spectrum analysis. In many test data, the shaft speed does not exist directly, sometimes because there is no sensor installed, sometimes the shaft speed signal is missing due to the failure of the sensor. At this time, it is necessary to extract the information of lost shaft speed from the vibration response signal. In addition, the complex transmission chain system often involves the process of multistage gear transmission, and the measurement of shaft speed is often only aimed at the input or output shaft of the system. The fault information is only related to the speed of the shaft on which the component is attached. In this case, it is necessary to introduce a concept of synchronous acquisition of any shaft, that is, using the known instantaneous speed information of the shaft and the kinematics of the transmission chain, synchronously collect any axis in the system.

Bonnardot [1] et al. proposed a synchronous sampling method based on band-pass filter, which first separates the fundamental frequency component of the gear meshing frequency or one of its harmonics from the acceleration response. Then the phase of the analysis signal constructed by the separated response is used to resample the vibration signal so as to realize the axis synchronous sampling. In this method, the selection of frequency band for filtering depends on experience and visual judgment. In order to improve this, Combet [2] et al. provided an automatic program for selecting the best frequency band for instantaneous axis speed identification. In order to adapt to the large speed change, Urbanek [3] et al. proposed a two-step process based on spectral analysis and phase adjustment. In their process, the instantaneous velocity of the shaft is roughly estimated through spectral analysis. Then, the instantaneous axis speed identified by synchronous sampling is “straightened”. Finally, the “straightened ” vibration signal is used for band-pass filtering to separate the vibration modes of interest. Then the isolated vibration mode is converted back to the time domain for phase adjustment.

The combination of time and frequency analysis and Vold-Kalman filtering is another common method for instantaneous axis velocity identification. In this method, the initial estimation of axial velocity comes from spectral analysis, such as short-time Fourier transform (STFT), wavelet transform(WT) or Wigner-ViNe distribution (WVD). VKF uses initial shaft speed and appropriate bandwidth to extract velocity-related single-mode components from the whole vibration signal [4]. Then the extracted single mode component is used to synchronously sample and analyze the vibration signal.

There are many other studies on instantaneous axis speed identification and synchronous sampling. For example, in the multi-order probability method [5, 6], more than one harmonic order is used to estimate the axial velocity. The intrinsic periodic resampling method [7] uses the intrinsic mode function obtained from the empirical mode decomposition for resampling, in which it is assumed that the intrinsic function is uniquely related to the shaft velocity response. Readers can refer to the literature for more information on the instantaneous shaft speed detection of shaft-less speed measurement [8], which provides a detailed literature search and uses many practical examples to check the advantages and disadvantages or different methods.

II. EXTRACTION FO ROTATIONAL SPEED INFORMATION FROM VIBRATION RESPONSE BASED ON INVERSE FOURIER TRANSFORM

A. *Fundamental*

The method based on Fourier transform and inverse Fourier transform is one of the band-pass filtering methods, which is more flexible and accurate than traditional filtering methods.

The common method to extract the circumferential vibration information from the vibration signal is to isolate the signal related to the shaft operation from the time domain by convolution by band-pass filtering. Although this method is more intuitive, when the shaft rotation signal is small, a high-order filter must be used, which will lead to filter instability and divergence, especially when the sampling frequency is high and the filter cutoff frequency is low. In addition, the filtering process is a convolution process, and the inaccuracy of the end point is inevitable in the discretized signal of finite length. The method based on inverse Fourier transform eliminates most of the problems. Theoretically, the method based on inverse Fourier transform can achieve absolute filtering, that is, the signal within the pass frequency range is not affected, while the signal outside the pass frequency is completely suppressed, as shown in Fig. 1.

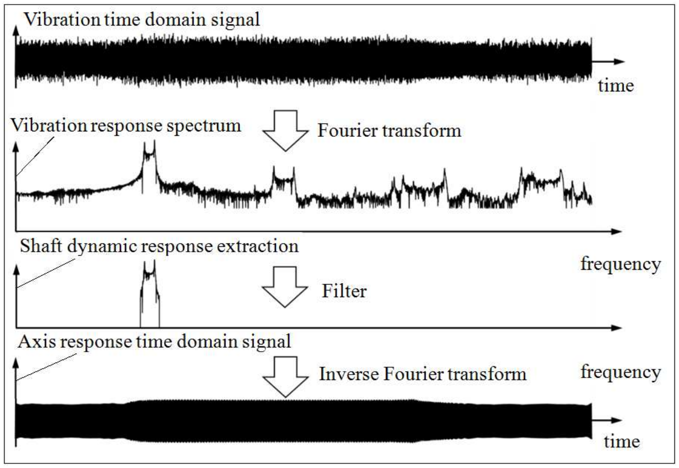

Figure 1. Fourier inverser transform filtering process

In addition, the method of inverse Fourier transform is not affected by sampling frequency and filter cutoff frequency. It should be noted that in order to ensure that the axis response signal after the inverse Fourier transform is a real signal, the principle that the real part is symmetrical and the imaginary part is anti-symmetric must be followed when suppressing the frequency response outside the pass frequency. Specifically, for the real periodic repetitive signal of an N discrete point (the imaginary part is zero), the transformation result is complex, only half of which is independent, the imaginary part of the other half is anti-symmetric distribution, and the real part is symmetrical distribution. For example, when N is an even number, as shown in Fig. 2, only the first $\frac{N}{2}+1$ points are independent, and the imaginary and real parts of the last $\frac{N}{2}-1$points are anti-symmetric and symmetrical to the $\frac{N}{2}-1$ points in the previous $\frac{N}{2}+1$ points, respectively. When N is odd, as show in Fig. 3, only the first $\frac{N+1}{2}$ points are independent, and the imaginary and real parts of the latter $\frac{N-1}{2}$ points are anti-symmetric and symmetrical with the $\frac{N-1}{2}$ points in the previous $\frac{N+1}{2}$ points, respectively. This relation is also applicable to the inverse Fourier transform, that is, in order to obtain the real periodic time domain signal from the inverse Fourier transform of the frequency domain signal, the imaginary part of the frequency domain signal must be anti-symmetric, and the real part of the frequency domain signal must be symmetrical.

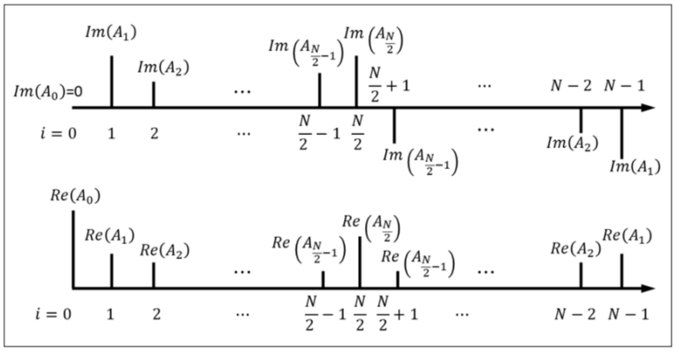

Figure 2. The property of FFT popularization fo periodic real functions, N is an even number

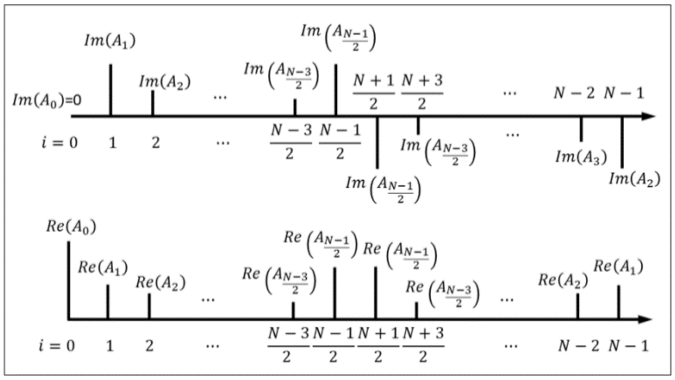

Figure 3. The property of FFT popularization fo periodic real functions, N is an odd number

B. *Basic steps of signal processing*

There are several main steps to extract the rotational speed information from the vibration signal and analyze it synchronously by using Fourier transform.

- Discrete response of vibration signal in time domain. The vibration signal is discretized according to a certain sampling mode, but the shaft velocity information is missing for some reason. However, the discretized vibration signal contains the rotational response components of the shaft, such as the vibration response caused by the rotation of the shaft or its harmonics.

- Fast Fourier transform frequency response. The discrete fast Fourier transform is applied to the time domain discrete signal, and the frequency domain response $A_i, i = 0,1,\ldots,N-1$ is obtained.

- Fixed frequency domain response. The frequency domain response is modified according to the frequency range of the shaft speed, and then the inverse FFT transform is carried out. This step is the key to realize filtering. Suppose the frequency information is contained between the frequency $[f_1, f_2]$, and the corresponding discrete frequency is $[n_1\Delta f, n_2\Delta f]$, Δf is the frequency resolution determined by the sampling parameters. In order to realize the band-pass filtering between the frequency range $[f_1, f_2]$, it is necessary to retain the frequency components between the $[f_1, f_2]$ in the FFT frequency response, while the other frequency components are set to zero. In order to make the inverse transform correspond to the time domain real function related to axial vibration, according to the description of the second step, for the case where *N* is even or odd, do the following operations respectively. When *N* is even, $A_k = 0, k = 0,1,\ldots,n_1-1;\ k = n_2+1, n_2+2,\ldots,\frac{N}{2};\ k = N-n_1+1, N-n_1+2,\ldots,N-1;\ k = \frac{N}{2}+1, \frac{N}{2}+2,\ldots,N-n_2-1$. When N is odd, $A_k = 0, k = 0,1,\ldots,n_1-1;\ k = n_2+1, n_2+2,\ldots,\frac{N-1}{2};\ k = N-n_1+1, N-n_1+2,\ldots,N-1;\ k = \frac{N+1}{2}, \frac{N+3}{2},\ldots,N-n_2-1$.
- The filtered axial response if obtained by inverse FFT.
- Hilbert transformation. The so-called analysis function is obtained by applying Hilbert transform to the filtered axis response signal. The analysis function is a complex function, in which the amplitude of the analysis function represents the instantaneous amplitude of the axis response signal, and the phase of the analysis function represents the instantaneous phase of the axis response signal.
- The instantaneous phase of the axis. According to the selection of the $[f_1, f_2]$ in step 3, the instantaneous phase of the axis response in step 5 is modified into the instantaneous phase of the axis operation. This is often a multiple relationship. If $[f_1, f_2]$ chooses an axis speed range, the two are the same. If the $[f_1, f_2]$ selects a frequency doubling of the axis speed range, the instantaneous phase of the axis response is also the same frequency doubling of the axis operation phase.
- Equal phase synchronization and discretization. With the instantaneous phase function, the equiaxed phase (or equiaxed circumferential angle) resampling or synchronous sampling of equiaxed discrete vibration signals can be easily realized.
- Synchronous analysis. Many synchronous analysis techniques can be applied to synchronously sampling discrete data.

C. *Example*

Fig. 4 shows the vibration response and Fourier transform spectrum of a variable speed motor running at a variable speed. From the spectral analysis of the vibration signal, it can be seen that although there is a spectral dispersion effect caused by the change of the axial velocity, there is no aliasing between the response modes, so it is suitable to use the inverse FFT method to extract the axial velocity.

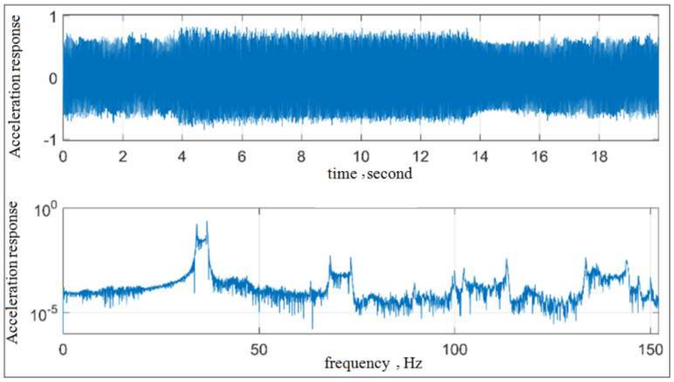

Figure 4. Vibration response

The Fourier spectrum of the response is filtered according to the given frequency range $[f_1, f_2]$, that is, the spectral values between the frequency range f_1 and f_2 are retained, while the values outside the frequency range are assigned zero, and the amplitude spectrum is shown in Fig. 5. The real and imaginary parts of the filtered spectral signal are obtained by inverse FFT transform, as shown in Fig. 6. In order to ensure that the imaginary part of the inverse FFT transform is zero, the “filtering” operation in the frequency domain must ensure the symmetry of the real part and the anti-symmetry of the imaginary part.

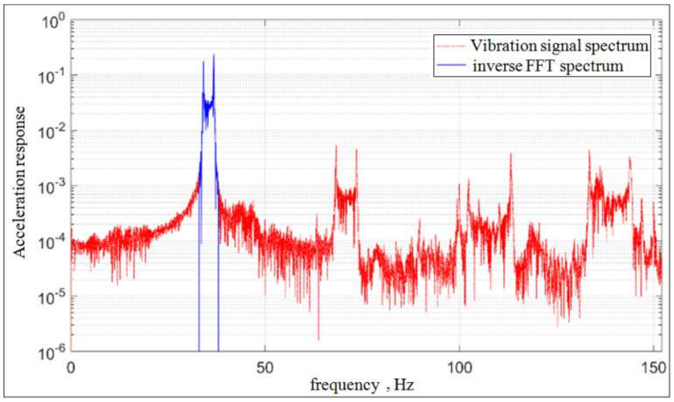

Figure 5. Band-pass filtering based on inverse FFT

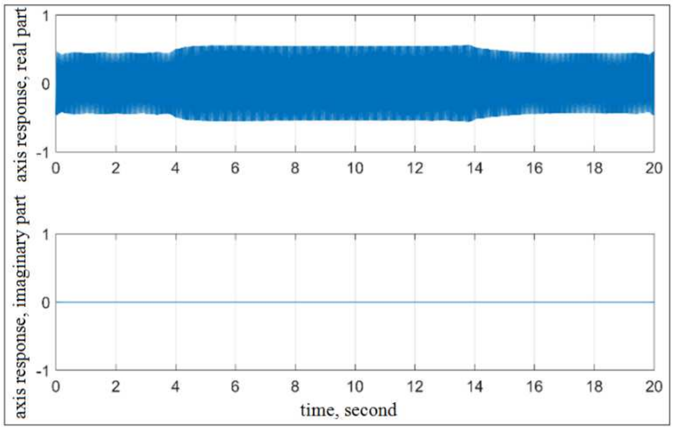

Figure 6. Inverse FFT signal after bandpass filtering

The real part of the inverse FFT obtained in this way should only be the single-mode response of the axial velocity vibration. Through the Hilbert transform, the instantaneous axis velocity can be obtained as shown in Fig. 7. The figure also shows the “real” axis speed obtained from the speedometer. It can be seen that the axis speed based on inverse FFT transform is very close to the real axis speed, with an error of less than 1%. The main error is near the starting point and the end point, which comes from the boundary effect of non-integer periodic sampling in Fourier transform.

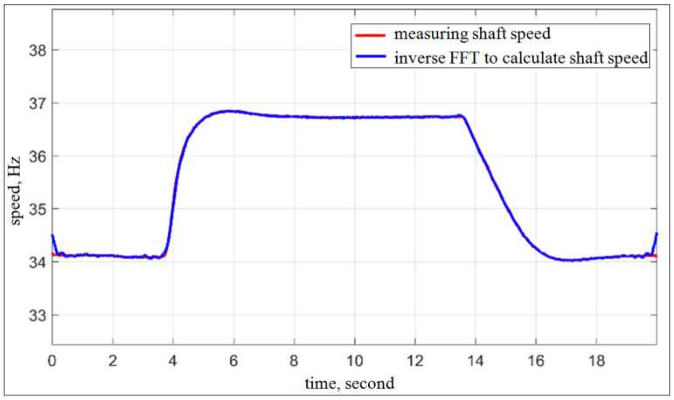

Figure 7. Comparison between inverse FFT Axial Speed identification and measured Shaft Speed

III. SYNCHRONOUS ANALYSIS OF SPEED SENSORLESS BASED ON SPECTRUM RECOGNITION

In the design of conventional band-pass filter, it is difficult to filter out all the modulation frequency components, especially the smaller side-lobe frequency components. In order to solve this problem, this section introduces a novel and simple method to extract instantaneous shaft velocity from vibration signals. For a given vibration signal, the spectrum is analyzed first. Then, the instantaneous axis velocity is identified from the spectrum by the maximum tracking algorithm. Through the numerical integration of the instantaneous axis velocity, the instantaneous phase is obtained and used for synchronous resampling in the numerical range. Then the subsequent synchronization analysis is carried out in the axial synchronization domain. In the case where there is no direct measurement of the shaft speed, the appropriate vibration response is usually used to extract the speed information. Among the existing methods, the maximum tracking method of vibration spectrum (such as literature [1] [2] [4]) is a technique that is easy to understand and implement. The vibration response (usually the acceleration response) is first converted into a spectrogram by the continuous –time response $\mathrm{x(t)}$ by ATFT analysis,

$$STFT(\tau,f)=\int_{-\infty}^{\infty}x(t)w(t-\tau)e^{-j2\pi ft}\,dt, \tag{1}$$

for a discrete sequence; otherwise,

$$STFT(m,\omega)=\sum_{n=-\infty}^{\infty}x(n)w(n-m)e^{-j\omega n} \tag{2}$$

where $w(t)$ is a window function.

In the actual operation, the graph is often realized by discrete Fourier transform with moving window, that is,

$$S(m,k)=|STFT(m,k)|, \tag{3}$$

there into

$$STFT(m,k)=\sum_{n=0}^{N-1}[x(n)w(n-m)e^{-\frac{j2\pi nk}{N}}] \tag{4}$$

In the formula, m and k are the time and frequency parameters in the spectrum, respectively. For a given sample F_s and STFT time shift $\mathrm{N_s}$, has,

$$t=mN_s\Delta t=\frac{mN_s}{F_s}, \tag{5}$$

and,

$$f=k\Delta f=\frac{kF_s}{N_s}, \tag{5}$$

It is a common practice for many researchers to estimate the frequency component from the spectrum. Suppose that the axis frequency $f_0(t)$ is a function that varies with time. In the spectrum based on acceleration response, the largest component of the response is not necessarily the axial response itself. Some other high-order frequency responses, such as gear meshing responses or harmonics, may have a good overall signal-to-noise ratio. In order to improve the detection accuracy, the maximum tracking can be carried out according to the frequency component of $cf_0(t)$, where c is a constant determined by the kinematics of the rotating machinery system. Once the instantaneous frequency is determined, the instantaneous axis frequency can be obtained by modifying the scaling factor c.

A process of synchronous analysis of rotating machinery using only vibration signals, as shown in Fig. 8. The basic steps of the brief flowchart of the process ate described as follows.

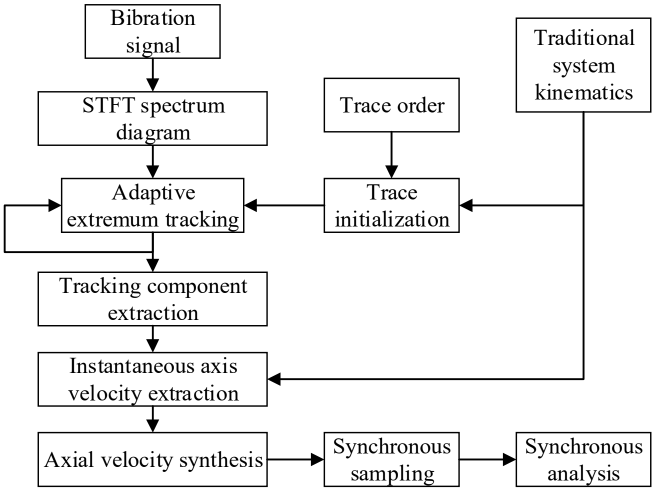

Figure 8. Analysis process

1. For a given vibration signal, the spectrum is calculated (usually SFTF analysis with appropriate time resolution and frequency resolution)

2. From the spectrum chart, determine the order and initial value of the maximum tracking.

3. Using the maximum tracking order of the previous step and the kinematics of rotating machinery, the current tracking boundary is determined adaptively, and the maximum current time step is searched in the spectrum.

4. Search the whole time domain, form the time history of the tracking frequency, and then use kinematics to determine the instantaneous axis speed.

5. Use the formula to synthesize the tachometer.

6. Synchronous sampling in digital domain according to the requirement of synchronous sampling points.

7. carry out synchronous average and synchronous analysis as needed to assess the health status of machinery.

The above method is used to identify the instantaneous speed of the high-speed shaft of the fan-gearbox. The spectrum of the vibration sensor from the high-speed bearing is shown in Fig. 9. According to the maximum energy criterion, the shaft speed tracking frequency is on the meshing frequency of high-speed gears. According to the structure of the gearbox, the number of pinion teeth in high-speed meshing is 27, thus the instantaneous frequency of high-speed gear meshing is shown in Fig. 10. The instantaneous speed converted to the high-speed shaft is shown in Fig. 11. The standard value of the high-speed axis is also shown in Fig. 11. The error between them is less than 0.7%. It can be seen that the instantaneous velocity identification of high-speed axis based on spectrum is feasible.

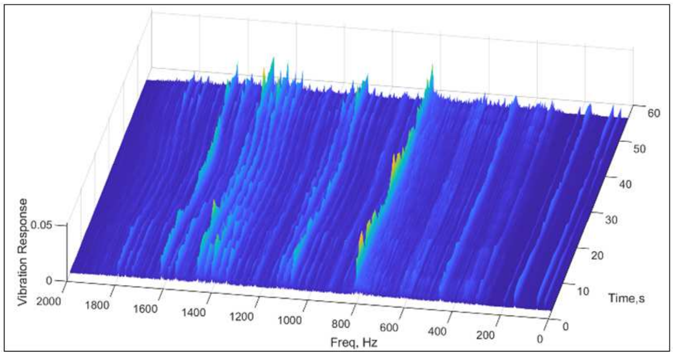

Figure 9. The spectrum of a fan gearbox

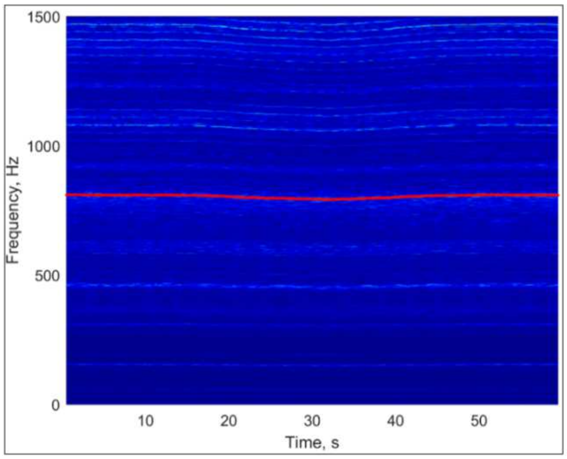

Figure 10. Instantaneous frequency of gear meshing at high speed based on spectrum recognition

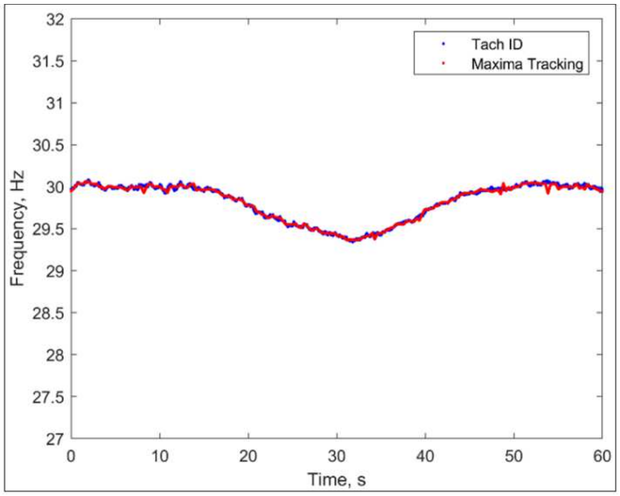

Figure 11. Instantaneous speed identification of high speed shaft

IV. SUMMARY

In the case of no shaft speed measurement, the effective acquisition of shaft speed information is the premise of speed-related fault feature extraction. Therefore, it is necessary to preprocess the vibration signal and extract the shaft velocity information from the vibration signal. In this paper, a signal preprocessing method for extracting shaft velocity information from vibration signals is described in detail. Based on the theory of signal processing, this paper summarizes the method of extraction shaft velocity signal without shaft velocity measurement, and verifies the effectiveness of the relevant theoretical methods and the accuracy of shaft speed extraction based on practical application cases.

The data preprocessing tool for extracting shaft velocity information from vibration signals solves the problem of obtaining shaft velocity change information without shaft speed measurement, and provides important speed information for experimental researchers. On the other hand, it is a prerequisite for later synchronous analysis and order analysis to effectively obtain shaft speed information.

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