Adaptive tacho information estimation for surveillance of rotatory machine under nonstationary conditions

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Abstract

Rolling bearing faults are the leading causes of downtime in rotary machines. In recent years, numerous and various vibration-based approaches have been put forwarded for rolling bearing fault detection. In the vibration-based techniques, order tracking-based methods are considered as very effective techniques. In the current reported order tracking methods, auxiliary devices are essential to obtain the instantaneous angular speed (IAS) of the machine. Aiming at this shortcoming, estimating IAS from vibration signals has been studied and some tacho-less order tracking (TLOT) techniques have been put forwarded. However, the effectiveness of the current available TLOT algorithms rely on the manually selection of the initial parameters for IAS estimation, which bring about user-friendliness. In order to tackle the aforementioned obstacles, a novel adaptive tacho information estimation method based on nonlinear mode decomposition (NMD) is proposed. In the proposed method, the nonlinear mode decomposition (NMD) method is improved and its computational burden is reduced. And then, the tacho information is adaptively estimated. The vibration signal collected from an aircraft engine is used for signal analysis and the effectiveness of the proposed is successfully validated.

1 Introduction

Rolling element bearing (REB) is especially important part of a rotatory machine, it usually works with variable load and speed, hence, failure is more possible happened here [2][3]. The failure of REB not only decreases machine working efficiency, but may also causes enormous lost in some extreme circumstances. In this way, it is of vital significance to detect the REB failure.

Vibration signal analysis is a kind of classic tool to detect machine fault [4], for the reason that vibration signal usually owns sufficient operating state information, it is viable to detect fault from it. However, most of the now existing methods are based on the assumption of stationary operating condition, which are impractical for accurate fault detection. To obtain a better fault detection results, the order tracking (OT) method [5][6] which is very suitable for speed variation condition is proposed and been widely studied. OT method transfers the non-stationary vibration signal in time domain into cyclostationary vibration signal in angular domain by resampling the non-stationary vibration signal with uniform angular increment, and fault can be accurately estimated from the order spectrum. Before resampling, the instantaneous angular speed (IAS) is needed. The conventional method uses auxiliary equipment [7], such as tachometer, to acquire the IAS information.

However, the auxiliary equipment brings extra cost and is not convenient in all conditions, and the tacho-less method is rapidly needed and catch considerable researchers' attention [8]. Zhao et al. [9] proposed a generalized demodulation based tacho-less OT method, this method combined the advantages of tacho-less OT method and envelope order spectrum, and could detect the REB fault under variation speed condition. To tackle with the inaccuracy of phase information estimation for OT method in large speed variation condition, Schmidt et al. [10] put forward a tacho-less OT methodology which is based on probabilistic approach, and the effectiveness is validated by both simulated and experimental signals. Sound signal also includes the REB healthy state information, Lu et al. [11] proposed a sound analysis-based method for bearing fault detection under speed fluctuation condition, the bearing fault can be uncovered from envelope spectrum of resampled signal successfully. In our previous study [12], a tacho-less OT tracking method which acquires better ISA information from adjacent vibration signal is proposed and can discover compound fault on wind turbines. Hu et al. [13] proposed an adaptive tacho-less OT method which is based on enhanced empirical wavelet transform (EEWM), this method introduces EEWM to analyse the characteristics of resampled signal and is relatively robust to noise.

Though tacho-less OT method shows great advantage to detect REB fault under speed fluctuation condition and researchers have make a lot progress about it, because of the unclear TFR of analysed signal caused by background noise and irrelevant components in the OT method, expertise knowledge and must be needed to extract the IAS information for resampling, which cannot ensure the detection accuracy and is inconvenient for real industry application. Hence, an adaptive IAS calculation strategy is urgently needed for tacho-less OT method. The Empirical Mode Decomposition (EMD) based fault detection method [14] is a kind of adaptive method and extracts mon-component via numerical approximation. However, because the phenomenon of spectral mixing among different modes caused by spectral overlaps between different components, biased IAS information for resampling and inaccuracy fault detection results may be obtained in some circumstance. Therefore, a more reliable adaptive IAS estimation strategy for tacho-less OT method in REB fault detection needs to be developed.

Aiming at the abovementioned requirement in the current existed tacho-less OT method for REB fault detection under speed variation condition, this paper proposed a new adaptive IAS information estimation strategy which is on the basis of Nonlinear Mode Decomposition (NMD) [15]. NMD is a hybrid product which combined the TFA and surrogate test, it shows great application prospect and could adaptively decompose a mixed signal into a set of mono-component which possesses clearly physical meanings. Our main works in this paper can be summarised as follows. First of all, the computation efficiency of NMD is meliorated to fit the high sampling frequency of the analysed vibration signal. Then, an adaptive IAS information estimation strategy is raised with the utilization of NMD. Last but not least, a noise-robust adaptive tacho-less OT method for REB fault detection under speed variation conditions is proposed, in which the expertise knowledge for IAS information extraction is not need and a broad industry application can be seen.

The remaining paper is organized as follows. In section 2, the theory of improved NMD is introduced and the detailed implemented procedures of our proposed method are given. In section 3, the validity verification of proposed method is given by the field test data experiments. And a conclusion is drawn in section 4.

2 The theory of meliorated NMD and implementation of the adaptive tacho-less OT method

In order to adaptively calculate the IAS information for resampling in a tacho-less OT method, the NMD theory is introduced in our study and elaborated in this section. And then, the realization process of the corresponding tacho-less OT method for REB fault detection is given.

2.1 The improved NMD theory for adaptive extraction of IAS information

As mentioned before, the EMD based IAS information extraction strategy is not robust in some cases, and an advanced technique is urgent to developed for tacho-less REB fault detection. The NMD is a newly developed method integrating with the advantage of parameterized TFA and surrogate test, it could decompose a complex signal into a series of physically meaningful oscillations. Therefore, it’s possible to adaptively extract IAS information using NMD.

The whole frequency range in TFR of analysed signal is searched in original NMD method, for a high sampling vibration signal, this is not necessary and takes long time. Hence, the NMD method must make some improvement in calculation speed for adaptive IAS information extraction. The detailed illustration of our improvement on NMD method is given in our former works [16], and the basic thinking is as follows. For the reason that the interested harmonics won't exist in the entire frequency range, and frequency searching range can be restricted to a special area decided by some equations which takes the peaks of TFR into consideration. With calculation efficiency of NMD method improved, the procedures of adaptive IAS information extraction strategy can be drawn like this.

Step 1: obtain the TFR of the REB vibration signal via Short-Time Fourier Transform (STFT).

Step 2: using Fourier transform surrogates test method to distinguish the extracted reference component from the noise.

Step 3: extract the subharmonics of the reference component, and investigate the consistency of the subharmonics by time-shifted surrogate.

Step 4: confirm the fundamental harmonic and find its possible higher order harmonics through consistency test.

Step 5: obtain the fundamental signal and its harmonics for further analysis.

Repeat step 3 to extract all of its harmonic signals from the TFR plane. Continue to perform the above steps on the residuals of analysed signal until a stopping criterion is satisfied. For details of the NMD method, please refer to [15].

2.2 The realization process of NMD based tacho-less OT method for REB fault detection

The meliorated NMD method are shown in last subsection, and the realization process of NMD based tacho-less OT method for REB fault detection can be summarized as follows.

Procedure 1: Utilize the meliorated NMD method to adaptively calculate the IAS information from the vibration signal.

Procedure 2: Resample the analysed signal with the obtained IAS information. In this way, this non-linear and non-stationary signal is transformed into cyclostationary signal in angular domain.

Procedure 3: Figure out the order spectrum with conventional means, such as Hilbert demodulation and spectral kurtosis.

Procedure 4: Recognize the fault type from order spectrum by analysing fault characteristic order.

3 The performance of the proposed method for aircraft engine tacho information estimation

3.1 An Overview of the Investigated aircraft engine

In this section, a difficult industrial case data is used to validate the effectiveness of the proposed method. The signals are acquired during a ground test campaign on a civil aircraft engine with two damaged bearings. The data is provided by Safran contest, Conference Surveillance 8, October 20–21, 2015, Roanne, France [1].

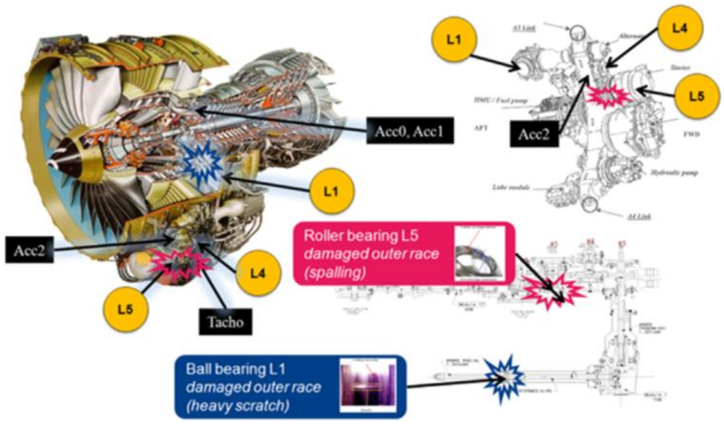

Figure 1: General overview of the engine and the accessory gearbox. [1]

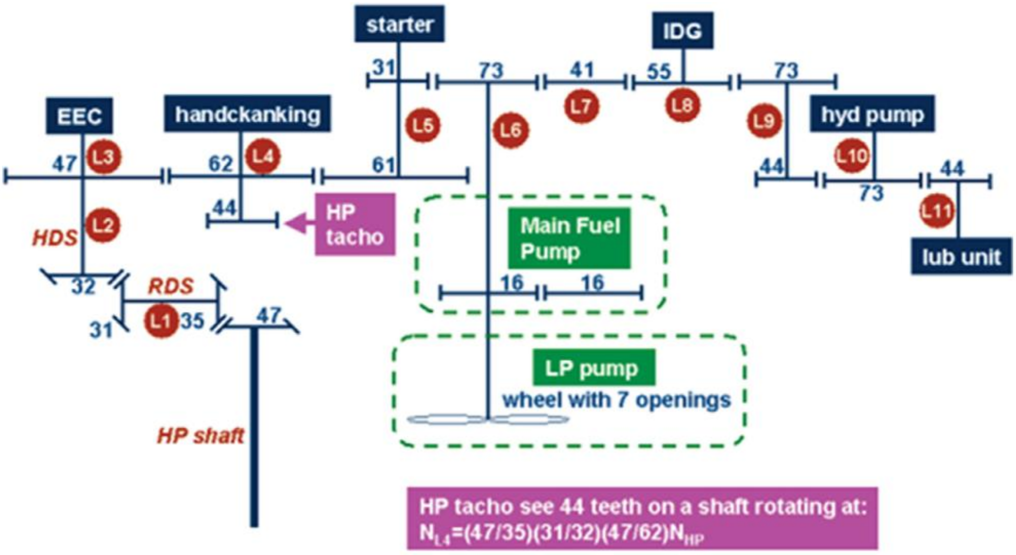

Figure 2: kinematics of the aircraft engine gearbox. [1]

An overview of the investigated engine and its accessory gearbox is demonstrated in Figure.1, and the kinematics of the accessory gearbox is depicted in Figure.2. The data used in section is collected by three sensors, named "Acc1", "Acc2" and "Tacho" in Figure.1, respectively. The sampling rate during signal collection process is 50 kHz and the sampling length is 200 s. The sensor "Tacho" is used to collect the rotating speed signal from shaft L4. One of the accelerometers is located on the intermediate case near the radial drive shaft and the other one is on the flange of the accessory gearbox in the vicinity of shaft L5.

3.2 The experimental results obtained by the proposed method

The partially enlarged drawing of the TFD of the original noise signal is shown in Figure 3, in which some frequency components are apparent. To conduct tacho-less order tracking on aircraft engines, it is very essential to extract one certain harmonic which is mono-component of the fundamental or higher harmonics of the rotating speed signal. In the conventional tacho-less order tracking techniques, the beginning of the interested harmonic is manually selected according to the fluctuation trend of IRF ridges in TFD. As a result, the current techniques are not applicable when the expertise knowledge is not available. To address the shortcomings encountered by the conventional techniques, the proposed method based on NMD is applied and its performance is demonstrated as follows.

Firstly, the dominant component with much higher energy in TFR is extracted as a reference component $x_r(t)$ by ridge detection, and the corresponding instantaneous amplitude $A(t)$, phase $\phi(t)$ and frequency $f(t)$ are reconstructed. And then, Fourier transform surrogate test against null hypnosis of noise is conducted to check whether the extracted signal is a true component. Totally 40 surrogates are created, the significance D_s of each surrogates and significance D_0 of the extracted component as depicted in Figure 4. All of surrogates with $D_s > D_0$, it indicates that the extracted component is true, therefore the null hypothesis of noise is rejected and continue the decomposition.

Further, the extracted dominant component $x_r(t)$ is assumed to be the fundamental one, and subsequently, time-shifted surrogate test against null hypothesis is conducted to investigate the independence between the extracted component $x_r(t)$ and its subharmonic candidates. The surrogate signals with a number N_s=20 are generated. The consistence $\rho_d^i(1,1,0)$ of the time-shifted surrogates and $\rho_0^i(1,1,0)$ of the candidate subharmonic with zero time shift $\mathrm{V}T_0 = 0$, are calculated as shown in Figure 5. For the candidates subharmonic of $x_r(t)$, all of the its time-shifted surrogates' consistency values are lower than the threshold, i.e. $\rho_d^{1/2} < \rho_{\min}$, which is equal to 0.25 [15]. In this circumstance, all of the candidate subharmonics are identified as false, because it does not pass the time-shifted surrogate test. Therefore, the extracted component $x_r(t)$ is taken as the fundamental harmonic of the rotating speed signal and regarded reference component for nonlinear mode extraction a step further. Similarly, based on the time-shifted surrogate test, the higher order harmonics are investigated and are also tested against the null hypnosis of noise. As a consequence, the second order harmonic passed the surrogate test and confirmed as a true component.

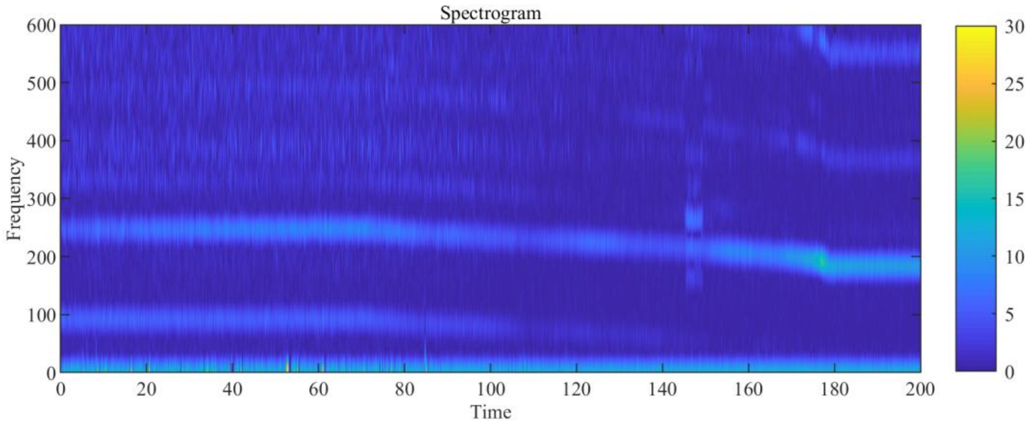

Figure 3: The partially enlarged drawing of the TFD of the original signal.

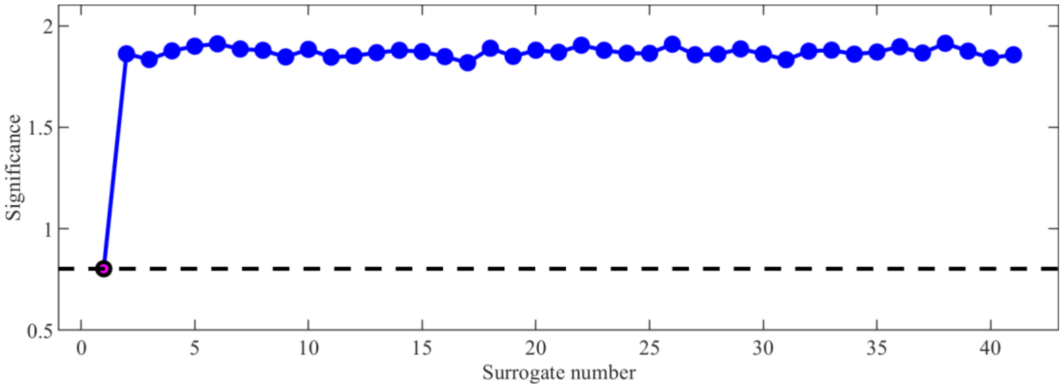

Figure 4: The Fourier transform surrogate test.

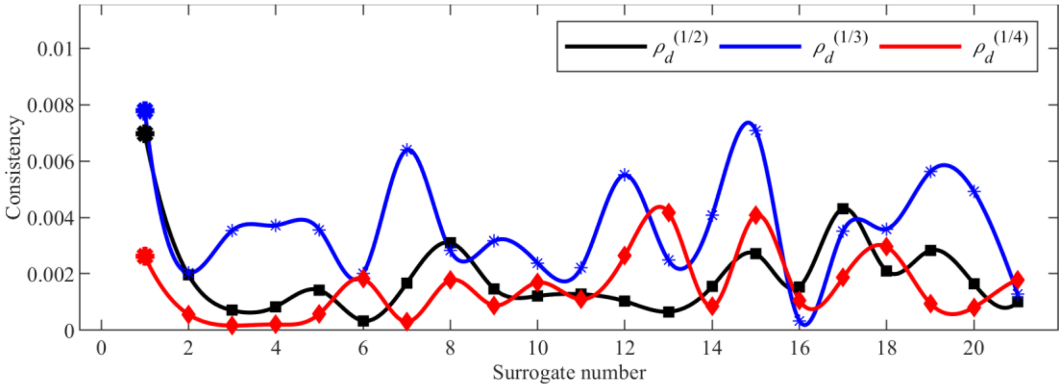

Figure 5: The consistency of the candidate sub-harmonics obtained by time-shifted surrogate test.

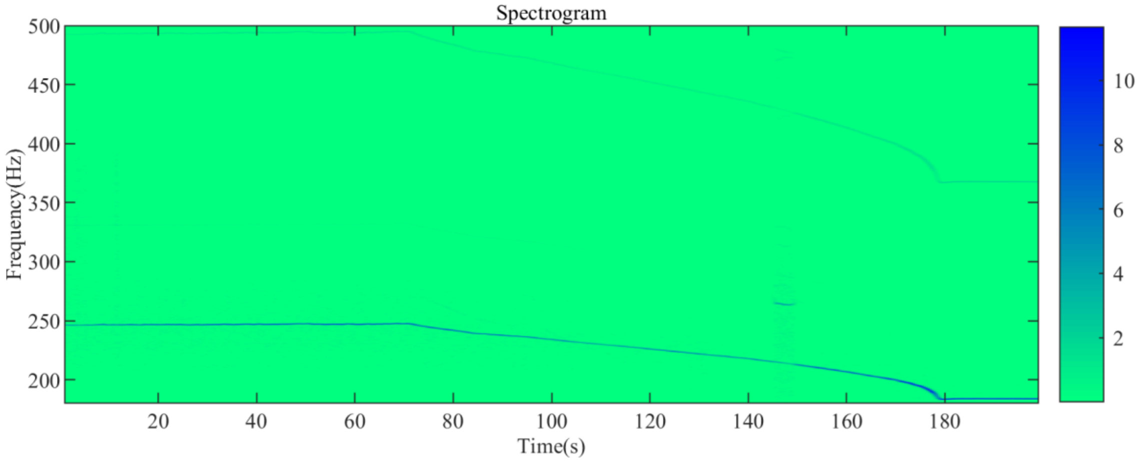

Figure 6: The extracted component in TFD domain.

The extracted rotating fundamental signal and its second order harmonic signal in TFD domain are depicted in Figure 6. Furthermore, the extracted fundamental component of the rotating speed signal is presented in Figure 7, while the extracted second order harmonic is depicted in Figure 8. On the basis of the extracted mono-component of the fundamental signal, the instantaneous frequency of the aircraft engine is calculated as shown in Figure 9. When compared with the instantaneous frequency estimation result reported in [1], the instantaneous frequency ridge is adaptively obtained by the proposed method successfully characterized the true fluctuation trend of the rotating speed.

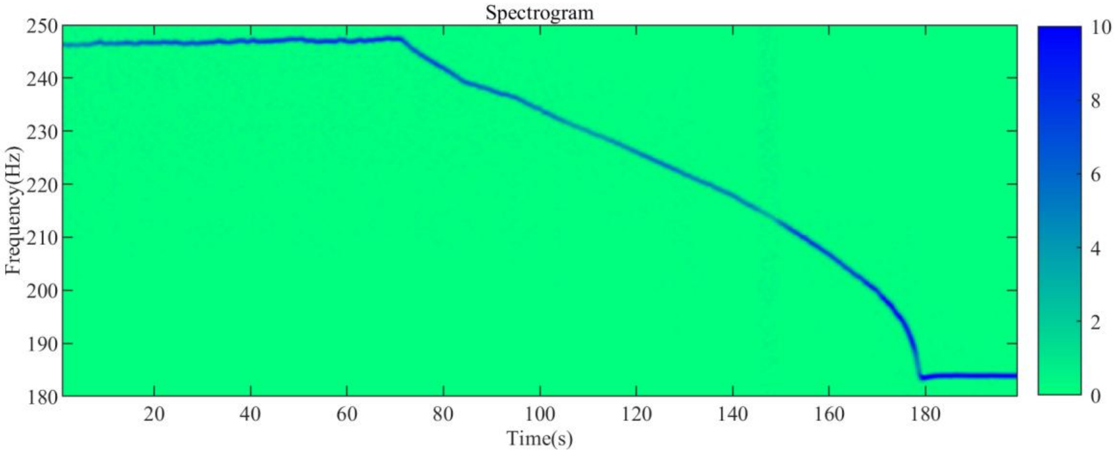

Figure 7: The extracted fundamental component of the rotating speed signal.

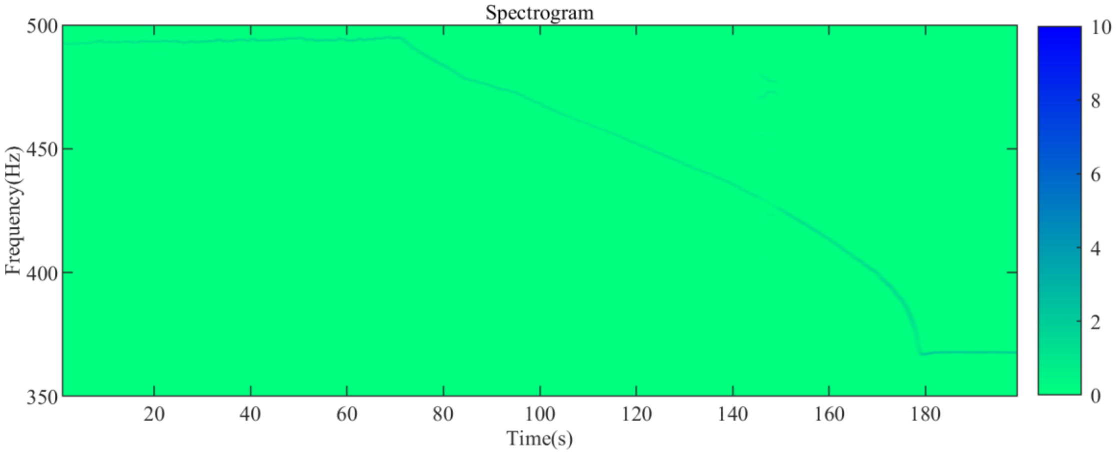

Figure 8: The extracted second harmonic of the rotating speed signal.

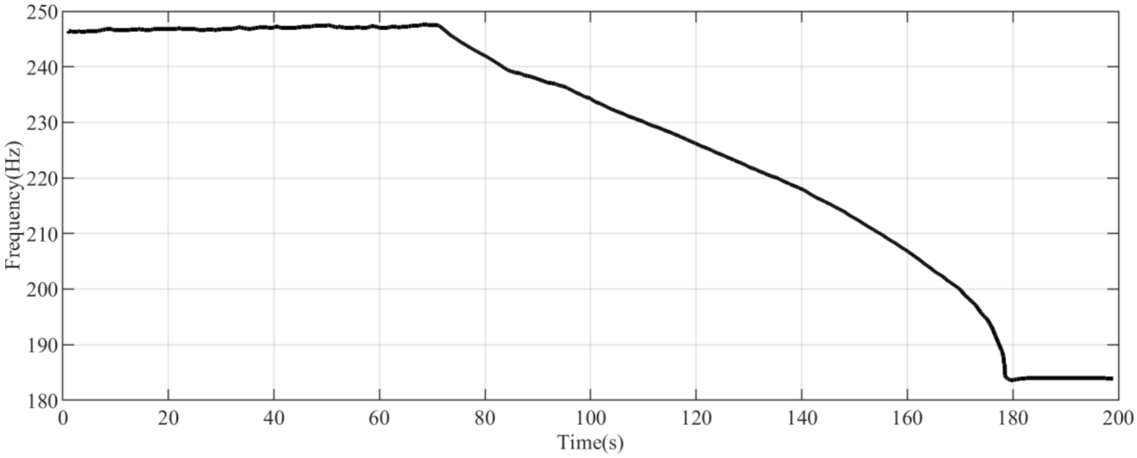

Figure 9: The estimated instantaneous frequency of the rotating speed signal.

4 Conclusions

To overcome the shortcomings of the conventional techniques for tacho information estimation under non-stationary operating conditions, a novel method based on improved NMD method is proposed in this paper. The merit of NMD method, which can adaptively separate mono-component from non-stationary signals and determine the fundamental harmonic, is inherited in our proposed method. The original NMD method is improved and the computational burden is reduced to make it applicable for aircraft engine vibration signal processing. On this basis, the shaft speed signal is adaptively extracted by improved NMD method and the tachometer information of the entire drivetrain is obtained. The effectiveness and improved features of the proposed are demonstrated by real aircraft engine vibration signals. The validation results indicate that the proposed method is more flexible for tacho information estimation, and provide a promising tool for fault diagnosis of rotating machines operating under nonstationary conditions.

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