Enhancement of Gear Fault Detection Using Narrowband Interference Cancellation

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Abstract. The development of enhanced fault detection ability for gearbox systems has received considerable attention in recent years. Detecting the gear fault easier is very important for maintenance action. This has driven the need in research for enhanced gear fault detection method. The goal is to extract periodic impulse signal from the very noise signal which mainly contains the narrowband signals. This can be done by enhancing the impulsive signals while suppressing the narrowband signals. This paper used a new method, Narrowband Interference Cancellation, to detect the gear fault. This method reserves the impulsive signal produced by gear fault and removes the other signals out. The methodology is demonstrated on a gearbox run-to-failure test. The results show that Narrowband Interference Cancellation can enable the gear fault detection easier.

1. Introduction

Gearbox is a key component in drive transmission systems, such as: mining machines, helicopters, and wind turbines. Any defects in gearbox will lead to catastrophic failure and results in a loss of production. So, detecting the gearbox defects as easy as possible to avoid fatal breakdowns of machines and reduce the cost are essential. Vibration analysis is the general technology applied in gearbox condition monitoring. Gear fault detection has been researched over many years. Many features based on the time synchronous averaging (TSA) have been proposed and the detail information can be found in [1]. Wang and Wong used autoregressive (AR) model to remove the regular toothmesh pattern for enhancing the impulse signal produced by gear fault [2]. Endo and Randall [3] proposed the use of minimum entropy deconvolution (MED) technique to enhance the ability of the existing AR model based filtering technique to detect localized faults in gears. Under this fundamental, some other revised AR models are also developed to detect the gear fault under constant load [4, 5]. Then, Yang and Makis further developed a ARX model based gearbox fault detection and localization under varying load conditions. This method considers load as additional information and tests validated it can be used in real situations [6].

The main objective of AR model based filtering is to separate the deterministic signal and random signal which produced by regular gear mesh and gear fault respectively. Li et al. [7] used the energy ratio between the random components and the deterministic components as the feature for bearing prognostics under varying load and speed condition. This property assumes when the bearing operating condition varies, both the energy of deterministic parts and random parts will change in the same direction. Therefore, the energy ratio will be more robust to the varying operating condition. In order to validate this method in gear fault feature extraction under non-stationary condition, Zhang et al. [8] conducted two gearbox test-to-failure experiments and extracted the energy ratio. The results showed that energy ratio can effectively reflect the degradation trend in both stationary and non-stationary condition. The comparison to some traditional features further explained the effectiveness of this method. However, there is big room for researchers to develop more methods which can be used to enhance the gear fault detection and reduce the missing detection ratio. Recently,

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Bechhoefer [9] developed a new method called Narrowband Interference Cancellation (NIC) to enhance the periodic impulsive signal produced by gear fault. However, the varying speed will influence the effectiveness of NIC fault detection. So, this paper will use the time domain synchronous technique to enhance the NIC fault detection and further validate this method using gearbox run-to-failure data.

2. Narrowband Interference Cancellation

For gear faults, they will produce impulse signals with the relative characteristic frequencies. So the vibration signals collected from machines contain gear mesh, shaft rotation, bearing vibration and random noise. For the signals produced by gear and shaft, they are narrowband. But the impulse signals generated by gear faults are in a wideband. Usually, the gear fault signals are very weak compared to the gear mesh tones and shaft rotation. So, if we can cancel these narrowband signals, the gear faults will be detected easily. A machine system can be modelled as:

$$x(n) = s(n) + y(n) + v(n) \tag{1}$$

where

$s(n)$ is the signal of interest,

$y(n)$ is the signal associated with gear mesh, shafts rotation, e.g. interference,

$v(n)$ is random noise.

The interference signal is usually large compared to the signal of interest. It is necessary to remove the interfering signal $y(n)$ from $x(n)$ while preserving the signal of interest $s(n)$. Since the measured signal $x(n)$ and the interference signal $y(n)$ are correlated, one can estimate the interference using an optimal linear estimator:

$$\hat{y}(n) = \mathbf{c}_0^H \mathbf{x}(n-D) \tag{2}$$

$$\mathbf{R}\mathbf{c}_0 = \mathbf{d} \tag{3}$$

$$\mathbf{R} = E\left\{\mathbf{x}(n-D)\mathbf{x}^H(n-D)\right\} \tag{4}$$

$$\mathbf{d} = E\left\{\mathbf{x}(n-D)y^*(n)\right\} \tag{5}$$

where D is an integer delay operator. If $D=1$, then Eq. (2) is the LS forward linear predictor. If $\hat{y}(n) = y(n)$, the output of the filter is $x(n) - \hat{y}(n) = s(n) + v(n)$. This means we can completely remove the interference and only the desire signal and noise remains. In practice, signal $y(n)$ is not available. To overcome this obstacle, we can use a minimum means square error D-step forward linear predictor, such that:

$$e^f(n) = x(n) + \mathbf{a}^H \mathbf{x}(n-D) \tag{6}$$

$$\mathbf{R}\mathbf{a} = -\mathbf{r}^f \tag{7}$$

where

$$\mathbf{r}^f = E\left\{\mathbf{x}(n-D)x^*(n)\right\} \tag{8}$$

For this modelling, the components of the observed signal have the following properties:

• The signal of interest $s(n)$, the interference signal $y(n)$, and the noise signal $v(n)$ are mutually uncorrelated.

• The noise signal $v(n)$ is white.

• The signal of interest $s(n)$ is wideband and has a short correlation length (e.g. its impulsive).

• The interference signal $y(n)$ has a long correlation length: its autocorrelation length takes significant values over the range $0 \le |l| \le M$, for $M > D$.

In practice, the second and third properties mean that the desired signal and the noise are approximately uncorrelated after a certain small lag. These are precisely the properties exploited by the canceller to separate the narrowband interference from the desired signal and the background noise.

According to the first assumption, we have

$$E\{x(n-k)y^*(n)\} = E\{y(n-k)y^*(n)\} = r_y(k) \tag{9}$$

$$r_x(l) = r_s(l) + r_y(l) + r_v(l) \tag{10}$$

If the second and third modeling assumptions hold true, we have

$$r_x(l) = r_y(l) \quad for \ l \neq 0, 1, \ldots, D-1 \tag{11}$$

The exclusion of the lags for $l \neq 0, 1, \ldots, D-1$ in $\mathbf{r}$ and $\mathbf{d}$ is critical, and we have arranged for that by forcing the filter and the predictor to form their estimates using the delayed data vector $\mathbf{x}(n-D)$. From (5), (8), and (11), we conclude that $\mathbf{d} = \mathbf{r}^f$ and therefore $\mathbf{c}_0 = \mathbf{a}_0$. Thus, the optimum NBI estimator $\mathbf{c}_0$ is equal to the *D*-step linear predictor $\mathbf{a}_0$, which can be determined exclusively from the input signal $x(n)$. Then, the signal with interference removed is:

$$x(n) - \hat{y}(n) = x(n) - \mathrm{a}_0^H \mathbf{x}(n-D) = e^f(n) \tag{12}$$

which is identical to the *D*-step forward prediction error. This leads to the linear prediction NIC shown in Figure 1. For a full description of the analysis, we can see [10].

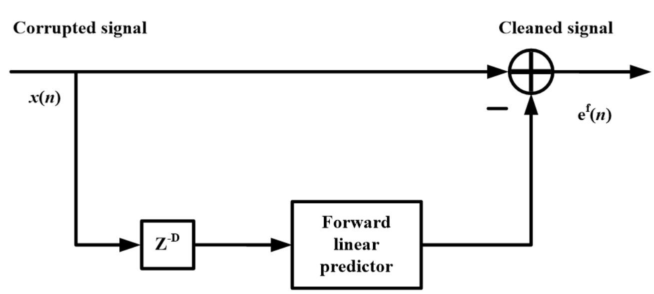

Figure 1. Block diagram of linear prediction NBI canceller.

3. Introduction

Figure 2 shows the experimental system used in this paper to verify the performance of the proposed method. The system includes a gearbox, a 4kw three phase asynchronous motor for driving the gearbox, and a magnetic powder brake for loading. The motor rotating speed is controlled by an electromagnetic speed-adjustable motor, which allows the tested gear to operate under various speeds. The load is provided by the magnetic powder brake connected to the output shaft and the torque can be adjusted by a brake controller. As shown in Figure 3, the gearbox has three shafts, which are mounted to the gearbox housing by rolling element bearings. Gear 1 on low speed (LS) shaft has 81 teeth and meshes with gear 3 with 18 teeth. Gear 2 on Intermediate speed (IS) shaft has 64 teeth and meshes with gear 4, which is on the high speed (HS) shaft and has 35 teeth. In order to acquire the speed and torque information, a speed and torque transducer is installed on the HS shaft.

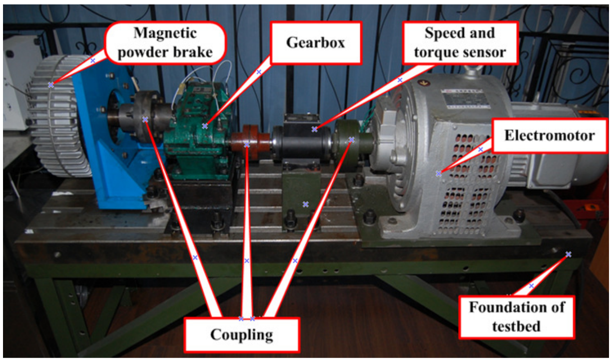

Figure 2. Test-rig of gearbox.

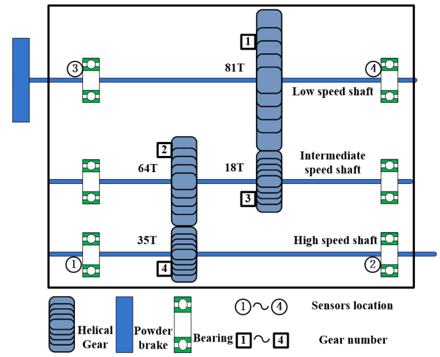

Figure 3. Structure of gearbox and the transducers location.

This experiment is a run-to-failure test. It operated from normal to failure. The whole process took 548 hours under speed 1200rpm and load 15N•m. The rotation speed and load were approximately stationary. In this test, the sampling frequency was 20KHz and the sampling time last 120 second. The sampling interval between two consecutive inspections is ten minutes. After test, the gearbox was disassembled. It was found that the main fault mode was wear. Gear 2, 3, and 4 had slight wear. Gear 1 has serious wear and some teeth were broken. The degradation process of gear 1 can be depicted as Figure 4.

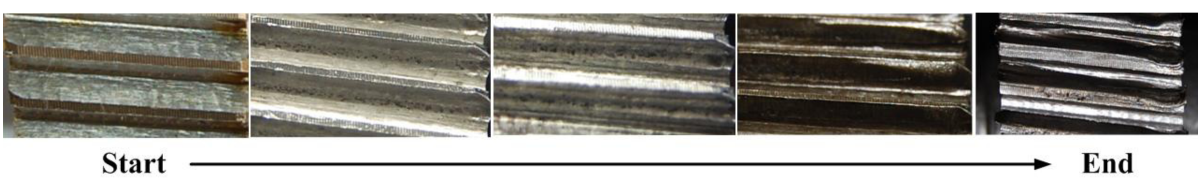

Figure 4. Fault propagation over time.

In order to demonstrate the effectiveness of proposed method, the data collected near the failure is selected as the analysis object. This data was collected at time point 3.241 (interval between two inspections is ten minutes). The data of sensor 4 which is near the gear 1 is used. Because the rotation speed has small fluctuation near the 1200rpm, the signal was resampled using time synchronous technology to remove the variation of rotation speed first. Then, it is processed by NIC to extract the impulsive signal produced by gear faults while suppressing the narrowband signal produced by no fault component. In this experiment, the parameters D and M of NIC are selected as 1 and 4096. The FFT spectrum of resampled signal can be seen in Figure 5(a). After NIC processing, the FFT spectrum can be seen in Figure 5(b).

In the Figure 5, GMF denotes gear mesh frequency. IS-LS denotes the gear mesh of IS shaft and LS shaft. HS-IS denotes the gear mesh of HS shaft and IS shaft. The Figure 5 showed that the narrowband signals which mainly the mesh frequency of HS-IS and its harmonics were suppressed. In order to further validate the proposed method, the detail spectrum of mesh frequency of IS-LS and its harmonics can be illustrated as Figure 6, 7, and 8.

Figure 6(a) is the spectrum around the mesh frequency with a frequency range from 170Hz to 250Hz (the first order mesh frequency of IS-LS is 197.5Hz). It shows that there is a IS shaft rotation modulation sideband occurring around the mesh frequency component. There is also a first order LS shaft rotation modulation sideband around the mesh frequency component. However, the amplitude of this first order sideband is very small compared to the amplitude of mesh frequency component. Figure 7(a) and Figure 8(a) are very similar to Figure 6(a). In these Figures, the sidebands are not dominant.

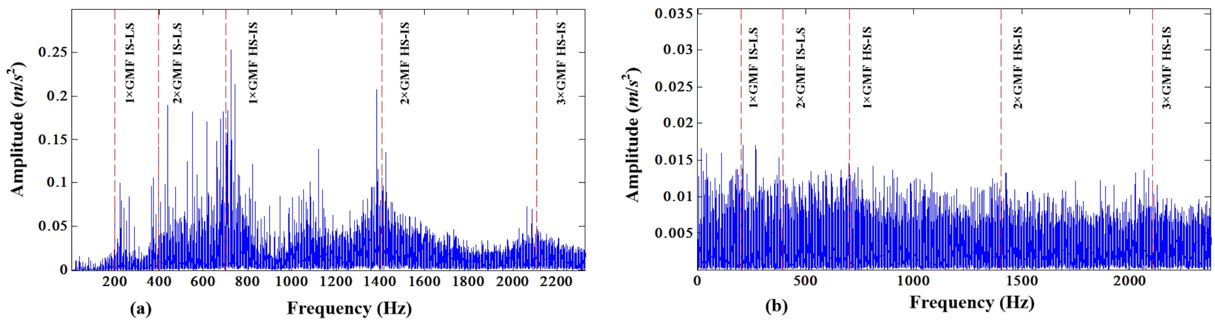

Figure 5. (a) FFT spectrum of resampled signal;
(b) FFT spectrum after NIC processing of resampled signal.

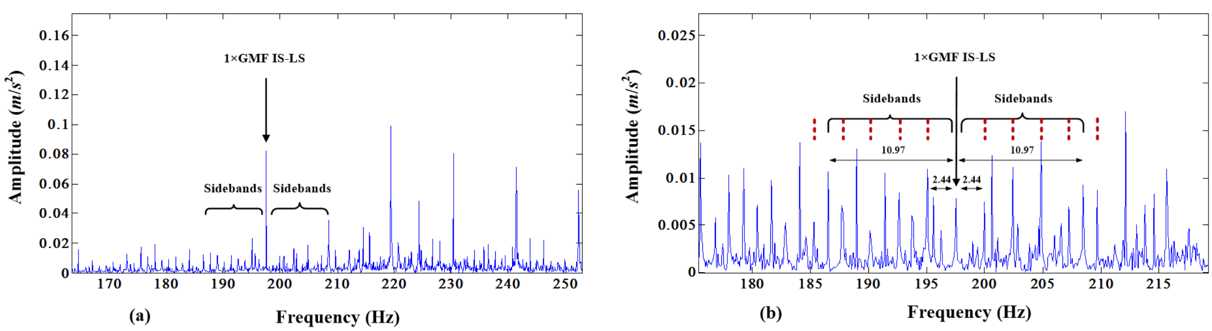

Figure 6. (a) Detail spectrum of first order IS-LS GMF before NIC processing;
(b) Detail spectrum of first order IS-LS GMF after NIC processing.

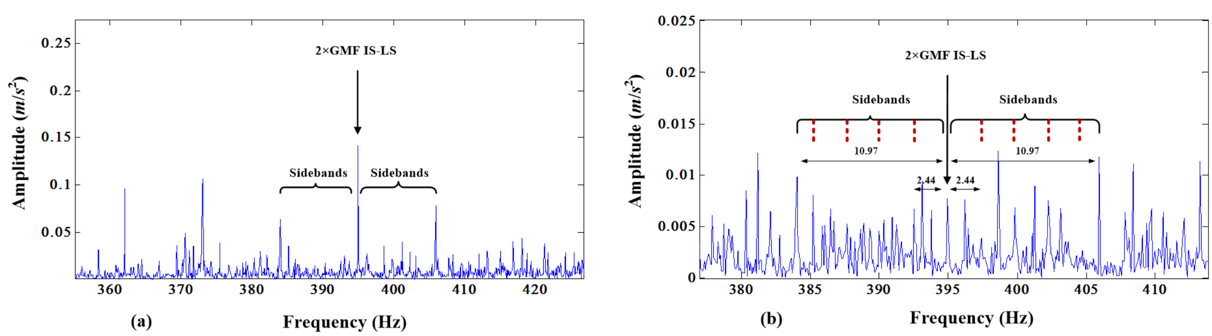

Figure 7. (a) Detail spectrum of second order IS-LS GMF before NIC processing;
(b) Detail spectrum of second order IS-LS GMF after NIC processing.

After NIC processing, the impulse signals are extracted while the narrowband signals are suppressed. Figure 6(b), Figure 7(b) and Figure 8(b) are the detail spectrum after NIC processing. A careful study of these figures indicates that the LS shaft rotation sidebands become dominant. In particular, the mesh frequency components are almost immersed by the sidebands. These Figures shows that some sidebands have higher amplitude than the mesh frequency component. This test indicates that NIC technology can enhance the impulsive signal produced by gear fault which leads to fault detection easier.

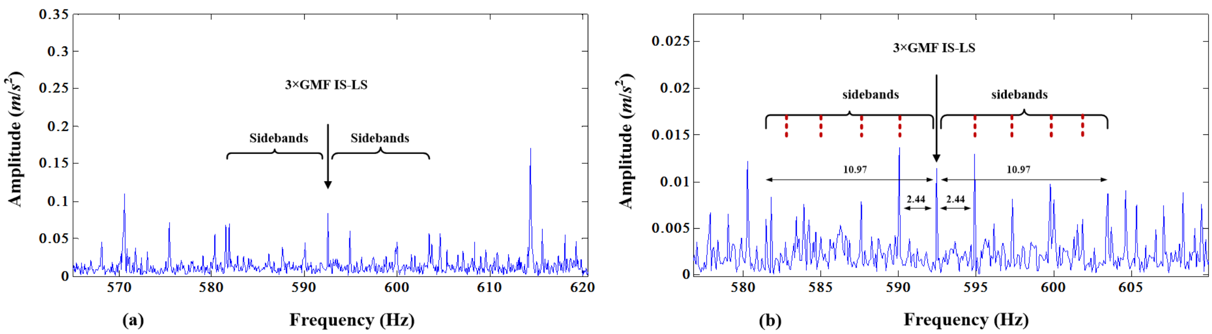

Figure 8. (a) Detail spectrum of third order IS-LS GMF before NIC processing; (b) Detail spectrum of third order IS-LS GMF after NIC processing.

4. Conclusion

This paper used a new method NIC that can enhance the periodic impulse signal produced by gear fault. Preprocessing the signal with NIC can enable the fault detection easier. It can remove the narrowband signal which has no relation to the fault. So, the sidebands that indicate the fault will become dominant in the FFT spectrum compared to original FFT spectrum. The gearbox run-to-failure test demonstrated the effectiveness of the proposed method. Additionally, the extraction of condition indicators from the NIC signal needs to be investigated. The condition indicators quantify the magnitude of a fault feature and allows for online/automated condition monitoring. The condition indicators are very useful for remaining useful life prediction. And, extracting robust condition indicators from NIC signal under varying load condition need to be investigated next step. Finally, the development of a NIC theory to optimally select the input parameters is needed. Currently, this *D* and signal length selection are an ad hock process.

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