Research and Application of BSS Algorithm on The Gearbox Fault Diagnosis Based on The MMI Criterion

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Abstract

This paper presented a kind of blind source separation (BSS) technology and applied it into the gearbox fault diagnosis through the blind mixing signal separation. The algorithm based on the natural gradient fixed step-length was used to calculate the statistical independent source signal estimate value, and successfully extracted the fault information according to the separation signal power spectrum based on the minimum mutual information (MMI) criterion. The gearbox fault condition can be diagnosed effectively through the experiment proved, which provided a new method to the mechanical equipment fault diagnosis and running state monitor.

Keywords: *BSS, MMI, natural gradient, mechanical equipment, fault diagnosis.*

1. Introduction

Through the monitoring and analysis to the mechanical equipment vibration noise, according to the noise sound level and the frequency changing to judge the fault position and reason has become one of the important means and methods, which has been widely applied. Among them, blind signal separation (BSS) [1] can separate each source signal estimation value under the assumption that each source signal is statistical independence each other from the mixed signal sample. At present, the several typical blind signal separation algorithms basically have Sejnowski and Bell's Infomax algorithm [2], natural gradient algorithm, Cardoso's EASI algorithm [3], inverse iteration algorithm, JADE algorithm [4] and Hyvarinen's Fast ICA algorithm [5], etc.

Blind signal separation algorithm is to establish cost function based on the information theory, higher order statistics[6], etc, and to optimize the objective function by using the optimization algorithm. Among them, the gradient algorithm is a kind of classic unconstrained optimization algorithm with the simple principle, and easy to realize with the equal variation characteristics, which can realizes the online calculation. So, the gradient algorithm [7] are widely used in the blind signal separation filed.This paper uses the technology to separate the aliasing vibration noise into irrelevant signals, thus provide the basis for the diagnosis of gearbox fault monitoring.

2. Blind source separation principle

Blind source separation can be expressed as the following formula. [8]

$$X(t) = AS(t) + N(t) \tag{1}$$

Among the formula (1), $S(t) = [S_1(t), S_2(t)...S_n(t)]^T$ is n d source vector, $X(t) = [x_1(t), x_2(t)...x_m(t)]^T$ is m d observation signal vector, $\boldsymbol{A}$ is $m\times n$ d mixing matrix, the elements express the mixed signal, $N(t) = [n_1(t), n_2(t)...n_m(t)]^T$ is m d noise. Blind source separation's goal is to estimate a separation matrix only according to the observation signal $X(t)$ without any prior knowledge.

$$Y(t) = WX(t) \tag{2}$$

Among the formula (2), $Y(t) = [y_1(t), y_2(t)...y_n(t)]^T$ is n d separation signal vector, if WA=P, P is a replacement array, which to get the aim to recover source signal. [9]

3. BSS algorithm based on MMI

The basic method of minimum mutual information [10] is to select suitable neural network weight matrix $\boldsymbol{W}$ to make output $Y(t)$ each component has minimum dependence. In an ideal situation until tends to zero, which to achieve the purpose of separation. Thus, we can use entropy to express the dependency among the signals [11]. And we can adopt the formula (3) to get.

$$I(W) = -H(X) - E\{\log|\det(W)|\} + \sum_{i=1}^{n} H(y_i;W) \quad (3)$$

We can make the mutual information amount $I(\boldsymbol{W})$ into minimum when selecting $\boldsymbol{W}$, which is MMI criterion. Because input signal entropy $H(Y;W)$ has nothing with the selecting $\boldsymbol{W}$. So, we can make it simply and build the cost function shown as formula (4).

$$\begin{aligned} L(\boldsymbol{W}) &= -E\{\log|\det(W)|\} + \sum_{i=1}^{n} H(y_i;W) \\ &= -E\{\log|\det(W)|\} - E\left\{\sum_{i=1}^{n} \log p(y_i)\right\} \end{aligned} \quad (4)$$

If we use different nonlinear transformation $g_i(y_i)$ to each component $y_i = \sum w i_j x_j$, and make $Z = (g_1(y_1),...,g_n(y_n))$ is output after transformation. Then the combination entropy $H(Z;W)$ of each component of Z can be expressed as formula (5).

$$H(Z;W) = H(X) + E\{\ln|\det(W)|\} + \sum_{i=1}^{n} E\{\ln g_i^{'}(y_i)\} \quad (5)$$

We can get natural gradient of combination entropy $H(Z;W)$ relative to separation matrix $\boldsymbol{W}$.

$$\begin{aligned} \frac{dW}{dt} &= \eta(t) \frac{\partial H(Z,W)}{\partial W} W^{-T} W \\ &= \eta(t)(W^{-T} - E\{\phi(Y)X^T\})W^{-T}W \end{aligned} \quad (6)$$

Among the formula (6), $W^{-T} = (W^{-1})^T$, $\phi(Y) = (-\frac{g_1^{''}(y_1)}{g_1^{'}(y_1)}),...,-\frac{g_n^{''}(y_n)}{g_n^{'}(y_n)})$, $\eta(t)$ is learning step length, expectation item $E\{\phi(Y)X^T\}$ can be instead of instantaneous value $\phi(Y)X^T$. Then the adaptive iteration formula to $\boldsymbol{W}$ is shown as formula (7).

$$W(t+1) = W(t) + \eta(t)(1 - \phi(Y)Y^T)W(t) \quad (7)$$

Formula (7) is iterative formula of natural gradient algorithm, it is thus clear that natural gradient algorithm can avoid $\boldsymbol{W}$ inversion, which making the calculation amount decreasing.

4. Gearbox fault diagnosis

Based on the minimum mutual information criterion of natural gradient separation algorithm, we carry out simulation to a gearbox fault diagnosis. [12] From the gearbox structure, it is comprised of the shaft, bearings, gears and spare parts, etc. So, we can acquire the vibration signal through installing sensors upon the gearbox, the collection signal is consisted by all kinds of vibration source signal and other noise interference, this kind of compound may be additive and multiplicative or other some more complex form. For simplicity, we can assume that the signal is linear through the transmission of the gearbox, the gearbox vibration signal can be said for the linear superposition signal of the gear meshing signal, bearing signal and noise signal, etc. According to the theoretical analysis, the gear meshing signal $s_1(t)$ can be represented as:

$$s_1(t) = \sum_{k=1}^{K} A_k(t)\cos(2\pi k f_m t + \varphi_k(t)) \quad (8)$$

Among the formula (8), f_m is meshing frequency, $\varphi_k(t)$ is phase, k is harmonic order times, and bearing fault vibration signal can be expressed as formula (9).

$$s_2(t) = \sin(2\pi k f_f t)(1 + \beta \sin(2\pi f_c)) \quad (9)$$

Among the formula (9), f_f is the fault characteristic frequency related with fault, f_c is shaft speed frequency. Meshing frequency f_m is integer times of the shaft speed frequency, the two frequences are related. Fault characteristic frequency f_f is rolling element bearing ring rolling in the drive frequency or its harmonic component, it is not relevant with the meshing frequency and shaft speed frequency. But the fault vibration signal $s_2(t)$ is fault characteristic signal or its harmonic and bearing vibration signal superposition, such as the formula (9) shows, so the gear meshing vibration signal $s_1(t)$ and fault vibration signal $s_2(t)$ is not related, they can be regarded as two independent component in blind separation model. [13]

For the meshing frequency f_m 1168 Hz, the gear shaft speed for 2920r/min, the rolling body spalling fault frequency f_f 256 Hz, [14] and we sample the signal in 10KHz in 0.4s, the waveform is shown as Fig. 1.

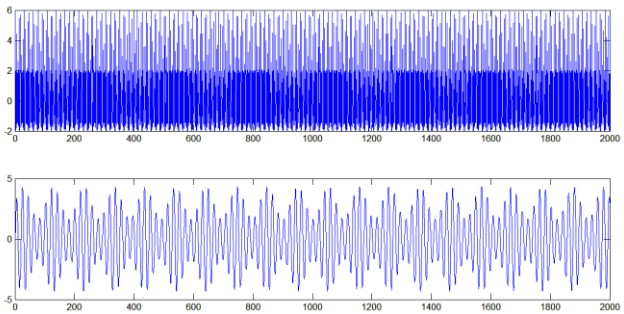

Fig. 1 Source signal.

The gear meshing vibration signal $s_1(t)$ and fault vibration signal $s_2(t)$ are blind mixed into the observation signal, which is respectively shown as Fig. 2.

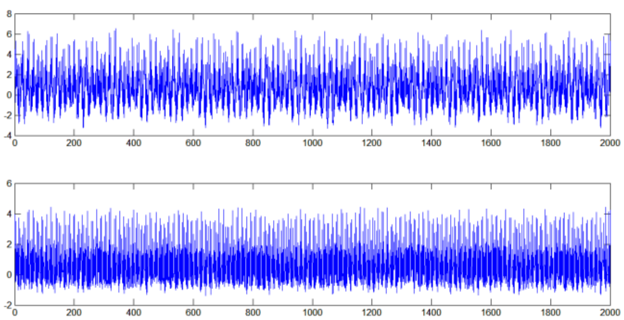

Fig. 2 Observation signal.

The observation signal power spectrum is shown as Fig. 3. The traditional vibration signal processing method is directly obtained and diagnosed through the observation signal. Because the characteristics of vibration source signal in the sensor is obtained during the mutual mixed or various nonlinear distortion, the noise jamming is big, transmission channel is complex, which often can not obtain the very good separation effect. [15]

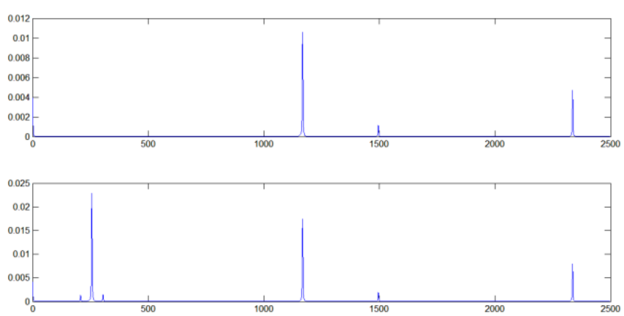

Fig. 3 Observation signal power spectrum.

We can separate the mixed signal by using the natural gradient algorithm, the separation signal is shown as Fig. 4.

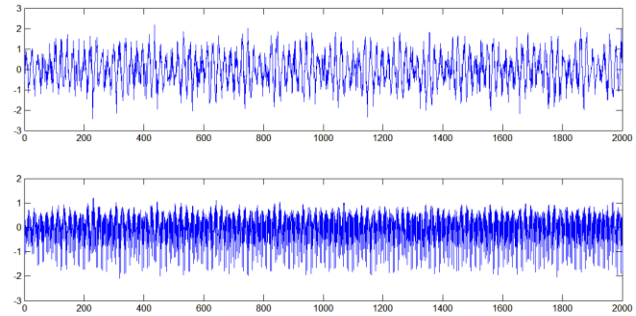

Fig. 4 Separation signal waveform.

When we carry out the power spectrum to the separation signal, the power spectrum of the separation signal is respectively shown as Fig. 5.

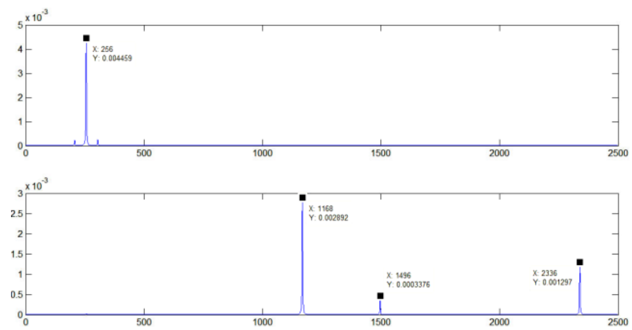

Fig. 5 Separation signal power spectrum.

From the Fig. 5 we can see, the power spectrum of the separation signal is approximation to the power spectrum of the source signal. The bearing fault frequency of 256Hz and the gear meshing frequency of 1168 Hz, its 2 times harmonic frequency can be reflected in the separated signal power spectrum. In addition, 1496 Hz signal is the composition result of the fault frequency and the spindle rotation frequency. The comparison result between the separation signal frequency and source signal is shown as Table 1.

Table 1: Comparison between the separation signal and the source signal

Data Type	f_f **(Hz)**	f_m **(Hz)**	$2f_m$ **(Hz)**	$\approx f_f + f_m$ **(Hz)**
Source signal	256	1168	2336	1496
Separation signal	256	1168	2336	1496

From the Table 1 we can see, the frequency separation result by MMI algorithm this paper presented is same as the source signal, which proved the algorithm has high separation precision. And we can judge the fault reason by using the algorithm.

5. Conclusion

In view of the gradient blind separation algorithm is a kind of online algorithm, which can realize the vibration signal online separation, and through the experimental analysis, the natural gradient algorithm can better separate the vibration signal, and we can adjust the value of the separation matrix according to the system's model characteristic, and get better separation results. Because the natural gradient algorithm has the equal changing characters, the amount of calculation, convergence speed and steady state performance is contradictory, step length in selecting also need comprehensive consider.

We used the BSS algorithm this paper presented to carry out the fault signal separation and fault diagnosis, the results show that based on the minimum mutual information criterion, the natural gradient blind source separation method not only can well separate blind mixed signal, but also can effectively realize the gearbox fault type diagnosis, which express the method has broad application prospects in the rotating mechanical equipment fault diagnosis.

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