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COMPOUND FAULT DIAGNOSIS OF GEARBOX BASED ON BLIND SOURCE SEPARATION AND EEMD-SVD

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ДІАГНОСТИКА СКЛАДНИХ НЕСПРАВНОСТЕЙ КОРОБКИ ПЕРЕКЛЮЧЕННЯ ПЕРЕДАЧ НА ОСНОВІ СЛІПОГО РОЗДІЛЕННЯ СИГНАЛІВ

Purpose. Blind source separation (BSS) is a new theory and method of vibration signal analysis and processing. With the development of science, blind source separation is more and more applied in the field of mechanical equipment fault diagnosis. In the research, it was applied in gearbox fault diagnosis, which is advantageous to separate mixed signal and make fault diagnosis.

Methodology. Based on the gearbox experiment platform of laboratory, first, we used the Intrinsic Mode Function–Singular Value Decomposition (IMF-SVD) source number estimation method to estimate the vibration source number, then we used the Ensemble Empirical Mode Decomposition-Singular Value Decomposition (EEMD-SVD) method to reduce noise and the Joint Approximate Diagonalization of Eigenmatrices (JADE) algorithm to separate the signals and extract the fault features. Lastly, we diagnosed the gearbox fault by further analysis.

Findings. Through many simulation experiments, we found that, in the case of high Signal to Noise Ratio (SNR)(0dB), the employment of the EEMD-SVD method followed by the JADE algorithm allows separating the vibration signal well and the separated signal only contains a small amount of noise. The gearbox fault diagnosis showed that the method has good results when diagnosing the mixed fault of the gearbox.

Originality. We made a study of combining the EEMD-SVD noise reduction method and the JADE algorithm to separate gearbox vibration signals. The further studies on this aspect may be helpful.

Practical value. The method has good accuracy and reliability when applied for the gearbox fault diagnosis. We will further study the application of blind source separation technology in gearbox fault diagnosis.

Keywords: *blind source separation, gearbox, EEMD-SVD, JADE, compound fault, fault diagnosis*

Introduction. The blind signal separation (BSS) is a signal processing method, which separates the unknown source signals from the observed mixed signals. It can be applied in the field of machinery fault diagnosis. The fault signal can be separated or extracted for subsequent processing of the signal and fault diagnosis [1, 2].

Nowadays the blind source separation theory has been widely used in data processing. It is mainly used in the language recognition, image processing, data mining, signal processing and other fields. With the development of science, the blind source separation becomes widely applied in the field of mechanical equipment fault diagnosis [3]. The fault diagnosis of a gearbox, especially the gears and bearings, is of great importance to the long-term safe operation. Some researchers and engineers are studying the fault diagnosis of gearbox based on the blind signal separation. Z Li, X Yan, Z Tian et al. presented a fault detection method for gearboxes using the blind source separation and nonlinear feature extraction techniques. They used the kernel independent component analysis (KICA) algorithm as the BSS approach for the mixed observation signals of the gearbox vibration to discover the characteristic vibration source associated with the gearbox faults and then used the wavelet packet transform and EMD to deal with the nonstationary vibrations to extract the original fault feature vector [4]. M.J. Roan, J.G. Erling and L.H. Sibul proposed the application of an information maximization based on the blind source separation algorithm (a type of ICA) to gear vibration measurements and shown that the algorithm is capable of tracking the higher-order statistics of the meshing signature using a single measure [5]. Jiang Y. and Zhi-Xiong L.I. described a condition monitoring and faults identification technique for rotating machineries based on independent component analysis (ICA) and support vector machine (SVM), and proved the proposed method is relatively effective [6]. These studies about the fault diagnosis of gearbox based on the blind source separation have achieved some results, but further studies are needed.

In this research, based on the experimental platform of the two-level reduction gearbox, we first use the IMF-SVD source number estimation method to estimate the vibration source number, then use the EEMD-SVD method to reduce noise and the JADE algorithm to separate the signals and extract the fault feature. Lastly we can diagnose the gearbox fault by further analysis. Moreover, we verified the feasibility of the method through simulation experiments, and finally applied it to the gearbox compound fault diagnosis.

Experiment method. Many algorithms of the blind source separation are derived from the background of noiseless. If there is noise, it is very difficult to estimate the separation matrix *W*, because we need to use the *m* observation signals to calculate the *m*+*n* unknown signals. But in the process of the operation of the machinery and equipment, there will be a lot of noise, making the observation signal polluted. Therefore, when the signals are separated, it is necessary to reduce the noise of the observed signals and ensure the correctness of the results. This research combines the EEMD-SVD noise reduction method and the JADE algorithm to analyze and process the signals.

The EEMD-SVD noise reduction method. The EEMD-SVD decomposition and noise reduction process is as follows:

(1) Ensemble Empirical Mode Decomposition of the original signal $x(t)$; we can get K *IMF* components and a residual component.

(2) Singular Value Decomposition of each IMF component; we get the corresponding singular value and mean square deviation of the difference of adjacent singular value sequence.

(3) To sort the mean square deviation from big to small, calculate the cumulative frequency and according to the cumulative frequency screening the IMF component. The cumulative frequency threshold is between 85 to 90%.

(4) To make the IMF component for noise reduction processing, and then adding together, the signal after the noise reduction is obtained.

The JADE algorithm. The JADE algorithm is a kind of separation algorithm based on four-order accumulation. Before the calculation of four-order accumulation, we must first make a pre-whitening of the mixed signal, that is, by a linear transformation *Q*, making the components of the mixed signal unrelated to each other. Then we get the signal after whitening $Z(t) = Qx(t)$. Thus, the four order accumulation matrix of the whitening signal can be defined as follows

$$C_Z(M) = \sum_{k,l=1}^{N} cum(z_i, z_j, z_k, z_l) m_{kl}, i, j = 1 \sim N \,. \quad (1)$$

Where m_{kl} is an element of an arbitrary dimension matrix *M*.

From the definition of four order accumulation, $C_z(M)$ is symmetric matrix. So it also can be expressed as

$$C_z(M) = V^T \Lambda(M) V \,. \quad (2)$$

This formula shows that the diagonal matrix $\Lambda(M)$ can be obtained by using the matrix V to make the two processing of matrix $C_z(M)$. Arbitrary select different $N \times N$ dimension matrix M_p of p, and calculate the four order accumulation matrix under $N \times N$ dimension matrix. Finally, a large matrix $C_Z(M_p)$ is formed by the accumulation matrix, then orthogonal separation matrix U by joint approximate diagonalization of the eigenmatrices algorithm. In summary, we can get the separation matrix $W = U^T P$.

JADE algorithm steps are briefly summarized as follows:

(1) Centralized the observation data $x(t)$, and whitening process, get $Z(t) = Qx(t)$.

(2) Joint approximate diagonalization the four order accumulation matrices $C_Z(M_p)$ of $Z(t)$, and get unitary matrix *U*.

(3) Calculate the separation matrix $W = U^T P$.

Experimental verification. Take the following 4 signals for simulation analysis, the waveform of original signal x_1, x_2, x_3 and x_4 is respectively shown in Fig. 1, *a–d*.

$$\begin{aligned} x_1 &= \sin(1100\pi t) + 0.5\sin(2200\pi t)\,; \\ x_2 &= (1 + 1.5\sin(50\pi t))\sin(240\pi t)\,; \\ x_3 &= \sin(480\pi t)\sin(100\pi t)\,; \\ x_4 &= 0.25\sin(100\pi t + 2t)\,. \end{aligned} \quad (3)$$

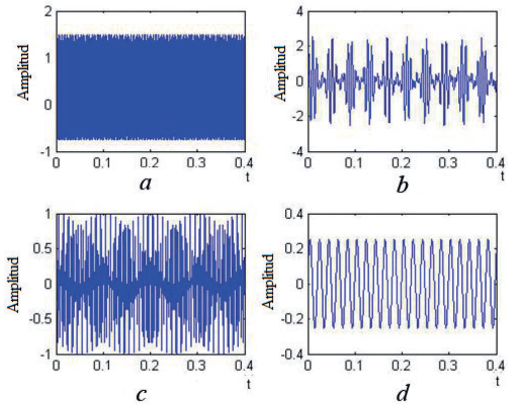

Fig. 1. Original signals: a – signal x_1; b – signal x_2; c – signal x_3; d – signal x_4

The mixed signal, which is respectively shown in Fig. 2, *a–d*, is obtained by random mixing, is then the observation signal is got by adding the random Gauss white noises whose mean value is zero and the standard deviation is 0.2 and 0.5 respectively to the mixed signal, shown in Fig. 3, *a, b*.

$$x(t) = s(t) + n_1(t) + n_2(t)\,. \quad (4)$$

In the simulation experiment 1, we first used the EEMD-SVD to reduce noise of the observation signals, and then used the JADE algorithm to separate the signals, and the signals time domain waveform in Fig. 4. The results that the signals were directly separated without noise reduction processing are shown in Fig. 5.

From Fig. 5, it can be seen that some of the original signals can't be identified, which is because that the observation signals direct separation will be affected by noise. The direct separation signal amplitude spectrum is as shown in Fig. 6, and a large amount of noise frequency components can be seen from Fig. 6. From Fig. 4, we can find that the signals, which are separated after the noise reduction have only a small amount of noise, and their waveform are very similar to the original signal waveform. The separation denoised signal amplitude spectrum is as shown in Fig. 7, it can be seen that the noise component has been largely removed, and the method has achieved good results, and the validity of the method is verified.

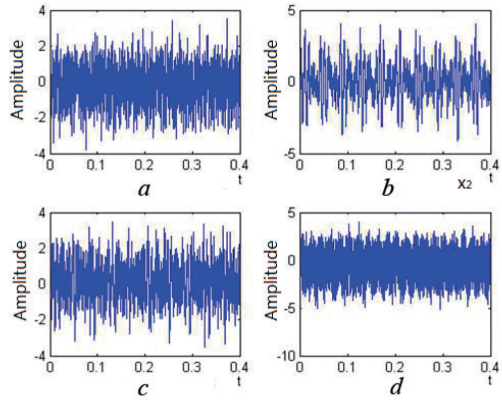

Fig. 2. Noise mixed signals: a – noise mixed signal x_1; b – noise mixed signal x_2; c – noise mixed signal x_3; d – noise mixed signal x_4

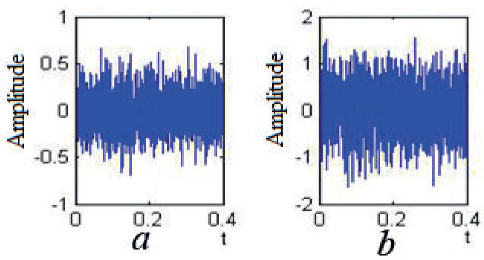

Fig. 3. Noises: a – noise 1; b – noise 2

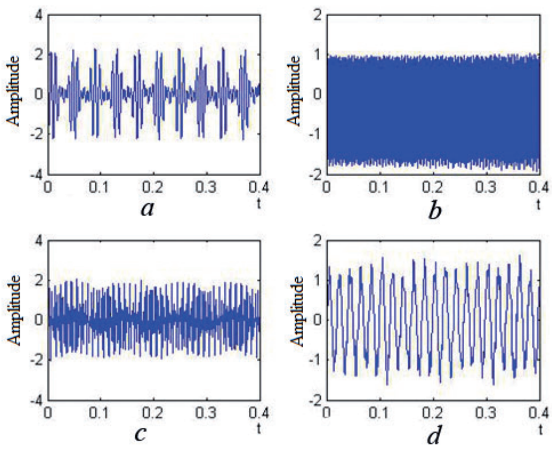

Fig. 4. Time domain waveform of denoised separation signals: a – denoised separation signal 1; b – denoised separation signal 2; c – denoised separation signal 3; d – denoised separation signal 4

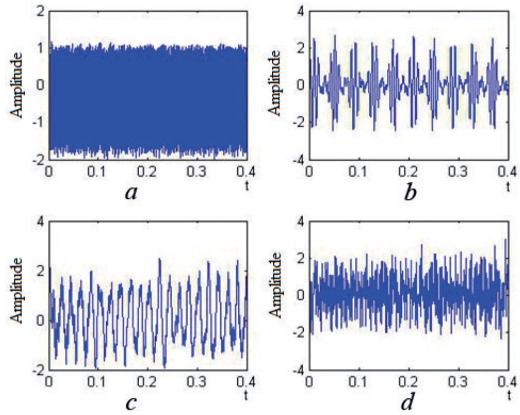

Fig. 5. Time domain waveform of direct separation signals: a – direct separation signal 1; b – direct separation signal 2; c – direct separation signal 3; d – direct separation signal 4

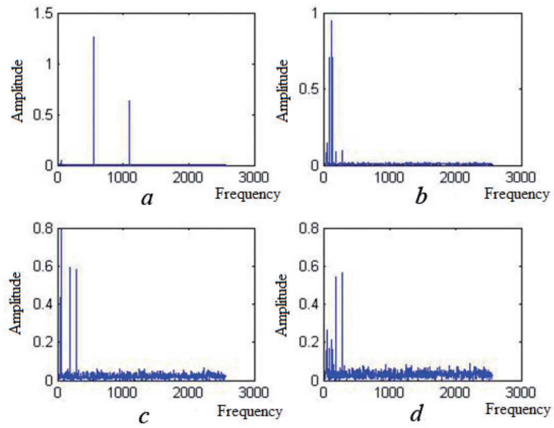

Fig. 6. Amplitude spectrum of direct separation signals: a – direct separation signal 1; b – direct separation signal 2; c – direct separation signal 3; d – direct separation signal 4

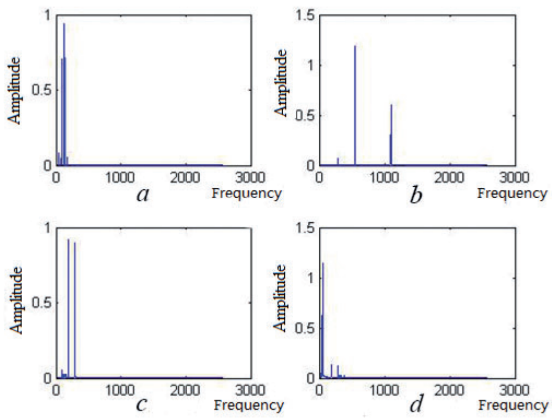

Fig. 7. Amplitude spectrum of denoised separation signals: a – denoised separation signal 1; b – denoised separation signal 2; c – denoised separation signal 3; d – denoised separation signal 4

Through many simulation experiments, we can find that, in the case of high SNR(0dB), first used the EEMD-SVD method and then used the JADE algorithm can separate the observed signals well and the separated signal only contain a small amount of noise. If the signal to noise is relatively low so that the signal is submerged, the method cannot get good results.

Compound fault diagnosis. Gearbox experiment platform is the secondary speed reduction gearbox system. Through replacing intermediate shaft pinion, we can set the working condition of the gearbox system: broken teeth fault of gear, gear eccentricity fault, roots of gear crack fault, etc. Gearbox transmission ratio is 8.62, and its internal structure diagram shown in Fig. 8. The transmission ratio of the input shaft and the intermediate shaft is 3.45, the number of gear teeth is respectively 29 (1st gear), 100 (2nd gear); the transmission ratio of the intermediate shaft and the output shaft is 2.5, the number of gear teeth is respectively 36 (3rd gear), 90 (4th gear).

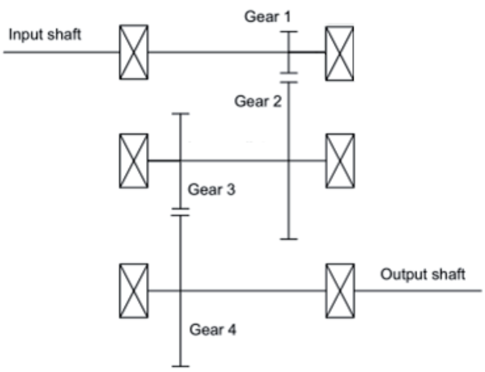

Fig. 8. Schematic diagram of the internal gearbox

Set the sampling frequency of 12800HZ, the sampling points of 12384 and the actual motor rotation frequency of 17.85HZ. Make the gearbox in the compound fault state of the broken tooth fault and the bearing outer ring fault. By calculated, the rotational frequency of the intermediate shaft is about 5.177HZ, the input shaft and the intermediate shaft gear meshing frequency is 517.65HZ, the intermediate shaft and the output shaft gear meshing frequency is about 186.37HZ, the outer ring fault characteristic frequency of the intermediate bearing is about 25.08HZ. Collect 8 channel signals at the same time and take 2 channel signals to estimate source number by the IMF-SVD source number estimation method. The singular value decline ratio is shown in Fig. 9. And we can know the estimated source number is 4 from the Fig. 9.

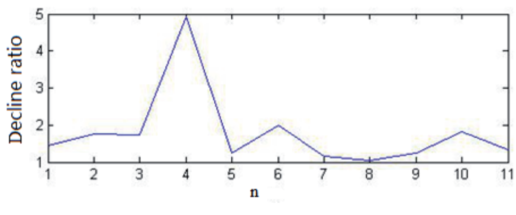

Fig. 9. Decline ratio

Take 4 sensor channel signals, and the time domain waveform is respectively shown in Fig. 10, *a−d*. First, we used the EEMD-SVD method to reduce noise and then used the JADE algorithm to separate the observed signals. The power spectrum of the separated signal is respectively shown in Fig. 11, *a−d*.

From Fig. 10 it can be seen that the fourth channel signal has serious impact, and the amplitude is relatively large. The impact interval is about 0.1930s. The frequency is 5.180HZ, almost equal to the rotational frequency of the intermediate shaft. Thus, it can be preliminary judged the existence of impact fault.

From the power spectrum of signal a) in Fig. 11, it can be seen that there are peaks and edge frequency bands at 518.8HZ and 1034HZ, and the peak of 1034HZ is higher than that of 518.8HZ. The two frequency respectively is the gear meshing frequency of the input shaft and the intermediate shaft (517.65HZ) 1 time and 2 times. In addition, there is a peak at 625HZ, the difference between 625HZ and 518.8HZ is 106.2HZ, which is about 6 times the frequency of the input shaft. Also there are peaks at 928.1HZ, 962.5HZ, 1000ZH and 1144HZ, the difference with 1034HZ are about integer (2, 4, 6) times the input shaft frequency. In addition, from the power spectrum of signal *b* it can also be seen the existence of edge frequency band with input shaft frequency interval at 518.8HZ and 1034HZ. This is similar to the fault feature of the shaft misalignment, and we can deduce that the input shaft has a shaft misalignment.

From the power spectrum of signal *b* in Fig. 11, it can be seen that there are peaks at 187.5HZ and 375HZ, and the two frequencies respectively are the gear meshing frequency of the intermediate shaft and the output shaft (186.37HZ) 1 times and 2 times. In addition, there is a peak at 1750HZ, and its amplitude is large, and there is a edge frequency band, after thinning, the peak at 18HZ, 10HZ and 25HZ are found, respectively approximately 1 time the input rotational frequency and 2 times, 5 times the intermediate rotational frequency. After analysis, the 1750HZ is a natural frequency of the gearbox. Therefore, we can conclude that the intermediate shaft pinion may have local fault. Because of the severe impact, so the local fault is likely to be a broken teeth fault.

From the power spectrum of signal *d* in Fig. 11, it can be seen that there are a larger peak at 100HZ and a smaller peak at 200HZ, which respectively are about the outer ring fault characteristic frequency of the intermediate shaft bearing (25.08HZ) 4 times and 8 times. We can judge the existence of the intermediate shaft bearing outer ring fault in gearbox.

Conclusions. Through the simulation experiment verification and the analysis of the gearbox compound fault diagnosis, it can be seen that the observation signals after EEMD-SVD noise reduction highlight the fault feature information. Then through the JADE algorithm for blind source separation, it can effectively separate the fault signal. Finally, we can diagnose the gearbox compound fault effectively after a follow-up signal analysis. It can be seen the method has good accuracy and reliability when applied for the fault diagnosis of gearbox in this research. We will further study the application of the blind source separation technology in the gearbox fault diagnosis.

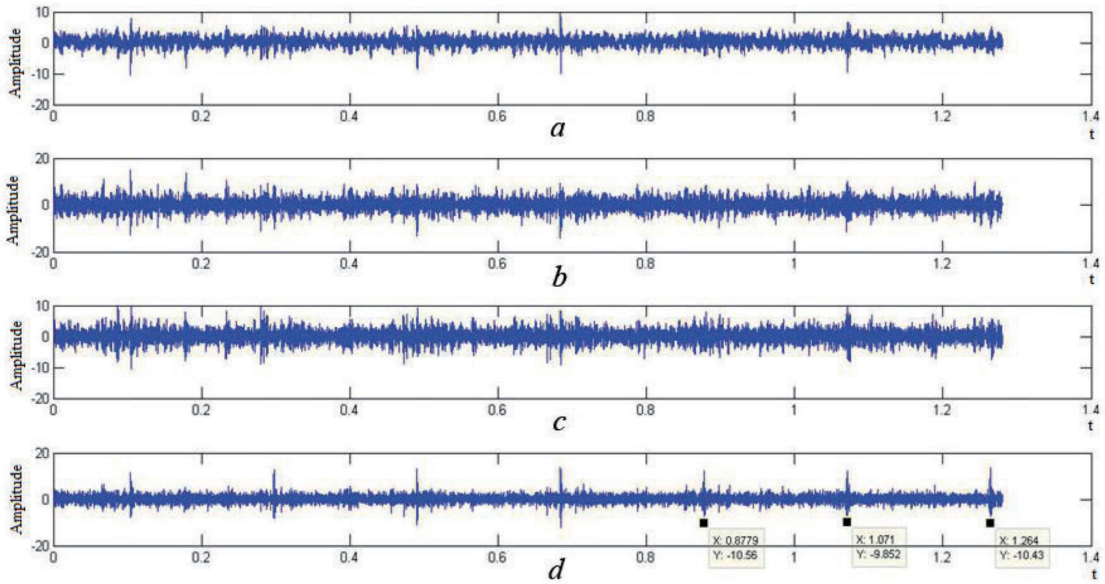

Fig. 10. Time domain waveform of original sensor channel signal: a – original channel signal of sensor 1; b – original channel signal of sensor 2; c – original channel signal of sensor 3; d – original channel signal of sensor 4

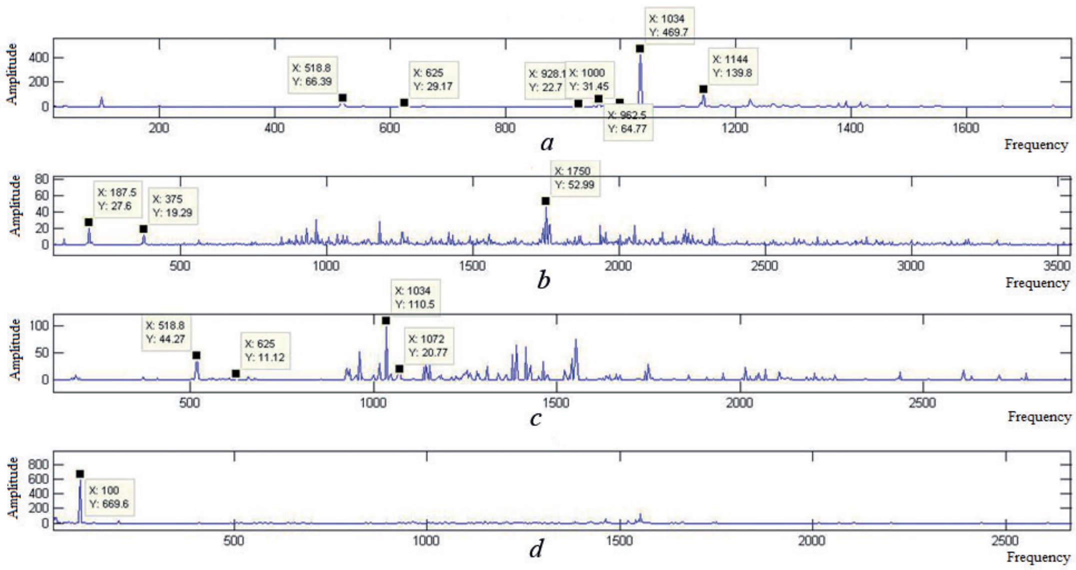

Fig. 11. Power spectrum of the separated sensor channel signal: a – separated channel signal of sensor 1; b – separated channel signal of sensor 1; c – separated channel signal of sensor 1; d – separated channel signal of sensor 1

References / Список літератури

1. Gelle, G., Colas, M. and Serviere, C. (2001), "Blind source separation: a tool for rotating machine monitoring by vibrations analysis", *Journal of Sound & Vibration,* vol. 248, no.5, pp. 865–885.

2. Keziou, A., Fenniri, H., Ghazdali, A. (2014), "New blind source separation method of independent/dependent sources", *Signal Processing,* vol. 104, no.6, pp. 319–324.

3. Gelle, G., Colas, M., Serviere, C. (2003), "Blind Source Separation: A New Pre-Processing Tool for Rotating Machines Monitoring?", *Instrumentation & Measurement IEEE Transactions,* vol.52, no.3, pp. 790–795.

4. Z Li, X Yan, Z Tian (2013), "Blind vibration component separation and nonlinear feature extraction applied to the nonstationary vibration signals for the gearbox multi-fault diagnosis", *Measurement,* vol.46, no.1, pp. 259–271.

5. Roan, M.J., Erling, J.G. and Sibul, L.H. (2002), "A new, non-linear, adaptive, blind source separation approach to gear tooth failure detection and analysis", *Mechanical Systems and Signal Processing,* vol.16, no.5, pp.719–740.

6. Jiang, Y. and Zhi-Xiong, L.I. (2011), "Research on the Blind Source Separation of Gearbox vibration and Its Application in Gear Fault Diagnosis", *Journal of Hubei University of Technology,* vol. 26, no.4, pp. 25–29.

Мета. Сліпе розділення сигналів є новим напрямом у теорії та методиці аналізу й обробці вібраційного сигналу. З розвитком науки сліпе розділення сигналів знаходить усе більше вживання в області діагностики несправностей механічного устаткування. У даній роботі воно застосовується для діагностики несправностей коробки перемикання передач, дозволяючи якісніше розділити змішаний сигнал і встановити причини несправності.

Методика. Дослідження проводилося на базі лабораторного експериментального стенду коробки перемикання передач. Спочатку, для визначення кількості джерел вібрації, використовується метод внутрішньої модової функції − сингулярне розкладання (IMF-SVD), далі використовується сукупний емпіричний метод розкладання по власних формах − сингулярне розкладання (EEMD-SVD) для зменшення перешкод і алгоритм спільної приблизної діагоналізації власних матриць (JADE) для розділення сигналів і визначення ознак несправності. При подальшому аналізі виявляється несправність коробки перемикання передач.

Результати. Велика кількість проведених моделюючих експериментів показала, що в разі значного співвідношення сигнал/перешкоди (SNR)(0dB), послідовне використання EEMD-SVD методу та JADE алгоритму дозволяє досить добре виділити сигнал, що, у результаті, містить лише невелику кількість перешкод. Діагностика коробки перемикання передач показала, що даний метод показує гарні результати при визначенні складних несправностей.

Наукова новизна. Вивчена можливість поєднання EEMD-SVD методу зменшення перешкод і JADE алгоритму розділення вібраційних сигналів коробки перемикання передач.

Практична значимість. Запропонований метод демонструє високу точність і надійність при діагностиці несправностей коробки перемикання передач.

Ключові слова: *сліпе розділення сигналів, коробка перемикання передач, EEMD-SVD, JADE, складна несправність, діагностика несправностей*

Цель. Слепое разделение сигналов представляет собой новое направление в теории и методике анализа и обработке вибрационного сигнала. С развитием науки, слепое разделение сигналов находит все большее применение в области диагностики неисправностей механического оборудования. В данной работе оно применяется для диагностики неисправностей коробки переключения передач, позволяя более качественно разделить смешанный сигнал и установить причины неисправности.

Методика. Исследование проводилось на базе лабораторного экспериментального стенда коробки переключения передач. Вначале, для определения количества источников вибрации, используется метод внутренней модовой функции – сингулярное разложение (IMF-SVD), далее используется совокупный эмпирический метод разложения по собственным формам – сингулярное разложение (EEMD-SVD) для уменьшения помех и алгоритм совместной приблизительной диагонализации собственных матриц (JADE) для разделения сигналов и определения признаков неисправности. При последующем анализе выявляется неисправность коробки переключения передач.

Результаты. Большое количество проведенных моделирующих экспериментов показало, что, в случае значительного соотношения сигнал/помехи (SNR)(0dB), последовательное использование EEMD-SVD метода и JADE алгоритма позволяет довольно хорошо выделить сигнал, который, в результате, содержит лишь небольшое количество помех. Диагностика коробки переключения передач показала, что данный метод показывает хорошие результаты при определении сложных неисправностей.

Научная новизна Изучена возможность совмещения EEMD-SVD метода уменьшения помех и JADE алгоритма разделения вибрационных сигналов коробки переключения передач.

Практическая значимость. Предложенный метод демонстрирует высокую точность и надежность при диагностике неисправностей коробки переключения передач.

Ключевые слова: *слепое разделение сигналов, коробка переключения передач, EEMD-SVD, JADE, сложная неисправность, диагностика неисправностей*

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