Comparison of Bearing Fault Diagnosis between Genetic VMD Algorithm and Permutation Entropy VMD

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Abstract: In VMD algorithm without parameter optimization function, it is necessary to decompose the signal by setting parameter the number of modal components K and artificial quadratic penalty factor α. In order to avoid the influence of the randomness and uncertainty of α and K on the correctness of VMD decomposition results, the method to optimize the parameter combination of K and α in VMD are proposed such as genetic algorithm and permutation entropy. In this paper, the genetic algorithm and permutation entropy are compared with Envelope spectrum analysis the decomposition results extracted from the bearing fault feature frequency and running time. But permutation entropy VMD has low running time because of permutation entropy VMD has few parameters according to the IMF without overlap, permutation entropy, and less iteration. Also the permutation entropy VMD can achieve local optimization, but unnecessarily global optimization. In genetic-VMD, genetic algorithm is used to optimize parameters by much iteration, so the running time is longer, but it has the ability of global optimization. The decomposition results demonstrate the genetic VMD algorithm and permutation entropy VMD are all effective.

Key Words: Comparison; Bearing Fault Diagnosis; genetic VMD; Permutation Entropy VMD, permutation entropy, envelope entropy

1. Introduction

Rolling bearing is widely used in aerospace, machinery manufacturing, industrial and agricultural production and other industries with rapid development. In these industries, rolling bearing is in high load operation state for a long time, and it is easy to fault [1][2]. Rolling bearing fault signal is a typical non-stationary nonlinear signal [3][4]. In view of this characteristic of this kind of signal and the problem that the fault information is submerged in strong background noise due to the bad signal acquisition environment, the advantages and disadvantages of each method are analyzed and a better bearing is found by comparing the parameters combination of K and α optimized by genetic algorithm and permutation entropy in VMD algorithm fault diagnosis method[4][5]. According to the frequency domain characteristics of VMD decomposition results, the constraint rules and screening strategies of decomposition layer K and quadratic penalty factor α are proposed to realize the automatic optimization process of VMD decomposition parameters. The optimal parameter combination of K and α obtained by the improved VMD algorithm is applied to the VMD algorithm of bearing fault diagnosis. Finally, the bearing fault feature frequency is decomposing from the envelope spectrum, which verifies the efficiency of the improved VMD algorithm[2].

2. G-VMD algorithm Introduction

In the VMD algorithm without parameter optimization function, the parameter mode K and penalty coefficient α are needed to be set for decomposing signal through experiments. G-VMD algorithm uses genetic algorithm to optimize the number of parameter modal components K and the quadratic penalty factor α of VMD algorithm, and finds the optimal combination of K and α through genetic algorithm to determine the minimum envelope entropy. The envelope signal can be obtained by decomposing the components of the signal and then demodulating the

e_j. The entropy is called envelope spectrum entropy, which can reflect the degree of fault information in vibration signal. X(j) (j = 1,2 , …,N), then the envelope spectral entropy e of the E_e can be expressed as[7][8]:

$$\begin{cases} E_j = -\sum_{j=1}^{N} e_j log e_j \\ e_j = a(j)/\sum_{j=1}^{N} a(j) \end{cases} \quad (1)$$

Where e_j is the normalized form of a (j), a (j) is the envelope signal of signal X(j) after Hilbert transformation.

When genetic algorithm is used to optimize parameters *K* (number of modal components) and *α* (quadratic penalty factor) in VMD algorithm, the process of parameter optimization can be realized in the following steps:

(1) The parameters of initialization algorithm include: population *size*, maximum genetic algebra *Gmax*, coding length *CodeL*, crossover probability *PC,* mutation probability *PM*, generation gap *gap*. Then set the search space range of the quadratic penalty factor *α* and the number of modal components *K*. The range of the quadratic penalty factor *α* is 100~5000, and the range of the number of modal components *K* is 2~10.

(2) The combination of penalty factor of VMD parameter and the number of components [*α, K*] is expressed as chromosome or individual in genetic space, the individual is expressed and the population is initialized by digital coding, the initialized individual is substituted into VMD operation, and the envelope spectrum entropy of each IMF component is calculated, and the minimum envelope spectrum entropy is taken as the fitness value of genetic algorithm, i.e. local minimum packet Entropy of complex spectrum.

(3)Select the individuals from the previous generation, form a new population, and reproduce the selected individuals to obtain the new generation of individuals. Then select individuals from the new population for cross combination, so as to produce new excellent population. In order to maintain the diversity of the population, individuals are selected from the population and mutated to produce better individuals.

(4)The fitness of the new population is calculated, and the iterations are continuously developed and updated to obtain the individuals of the global optimal population, so as to obtain the optimal combination of the influence parameters[α_0,K_0].

3. P-VMD algorithmn Introduction

3.1 P-VMD algorithmn principle

The P-VMD(Punctuation selection VMD) method combines the advantages of the variational mode decomposition (VMD) algorithm and permutation entropy algorithm (PE), and realizes the process of signal denoising and decomposition. The variational mode decomposition algorithm has been invoked two times, the first call and the permutation entropy algorithm are combined to realize the signal denoising process; the second call realizes the decomposition process of the denoising signal.

The implementation steps of P-VMD are as follows[9]:

(1) VMD decomposition method is used to decompose and process the collected signals, and *K* preset IMF components are obtained;

(2) The permutation entropy (PE) values of *K* IMF components decomposed by VMD are calculated respectively, and a threshold value ρ is set to judge whether each component is a useful component;

(3) Compare the PE value of each IMF component with the threshold value ρ, if PE value is greater than ρ, the modal component is useful signal, otherwise it is useless noise signal, the useful component is reserved, and the useless component is removed;

(4) Kalman filter method is used to smooth the selected useful components, and then reconstruct them to complete the process of signal denoising;

(5) The reconstructed signal is decomposed by VMD.

3.2 Parameter selection method of P-VMD

In order to smoothly extract the fault information and ensure that the fault information is decomposed without dispersing, it is hoped that the fault features are prominent and obvious, and the signal is accurately decomposed. That is, it is hoped that the mode parameter K is as large as possible without modal overlap with a suitable α. According to it, a constraint rule of K and α can be set: It is possible to find the quadratic penalty factor α so that the K components that are decomposed without modal overlap. The maximum K and the corresponding α are the appropriate value of decomposition layers and a suitable quadratic penalty factor.

It is determined by the following formula that the VMD decomposes whether each mode is overlapped[10][11]:

$$\sum_{i=1}^{K}\sum_{j=1}^{K}\left|I_k(i)\cdot I_k(j)\right| = 0 \quad (i \neq j) \qquad （2）$$

Where K denotes the value of modal decomposed by VMD, I_K *(i)* and I_K *(j)* denote the *i-th* and *j-th* modal components in the same decomposition, and " • " denotes the inner product operation of the i-th and j-th modals. If the equation(2) is satisfied, it means that no overlap occurs in the K modal decomposed by the VMD.

The screening strategy is based on the constraint rules of K and α in equation (3) as follows:

$$\begin{cases} X_m = Sort(Smooth(FFT)(I_k)) \\ X_m(1) < X_m(2) < \cdots < X_m(k) \\ \dfrac{Y_m}{\delta} \to Ljx, \dfrac{Y_m}{\delta} \to Rjx \qquad (Ljx < Rjx) \\ Ljx_{(n+1)} - Rjx_{(n)} \qquad \begin{matrix} k \in (3,9) \\ \alpha \in (1000, 8000) \end{matrix} \\ \min\left[Ljx_{(n+1)} - Rjx_{(n)}\right] > 0 \; n \in (1,k) \end{cases} \qquad （3）$$

Where I_k represents the *K-th* components of the signal that are decomposed by the VMD; X_m represents the peak abscissa of the IMF component spectrum processed by Smooth filtering, Y_m represents the ordinate; *Ljx* represents the abscissa of the left punctuation found in the IMF component spectrum after smooth filtering, *Rjx* represents the abscissa of the right punctuation.

The specific implementation steps of the constraint rules and screening strategies of two important parameters K and α in VMD decomposition are as follows:

(1) K starts from 9 and decreases one by one; α starts from 1000 and reaches 8000, and each increments by 500;

(2) Perform the Smooth filter processing on the frequency domain waveform of the K IMFs, and treat the frequency domain waveform abstraction as a normal distribution curve, and find the peak value of the peak, and record the peak coordinates as (X_m, Y_m);

(3) setting a threshold δ, the parameter η defines as peak value Y_m divided by δ, in this case δ is 20;

$$\eta = \frac{Y_m}{\delta} \qquad （4）$$

(4)Taking the value of η as the ordinate, find the two coordinate points corresponding to this ordinate in the frequency domain curve. According to the size of the abscissa of the two coordinate points, the two coordinate points are respectively recorded as a left judgement and right judgement as Fig.1.

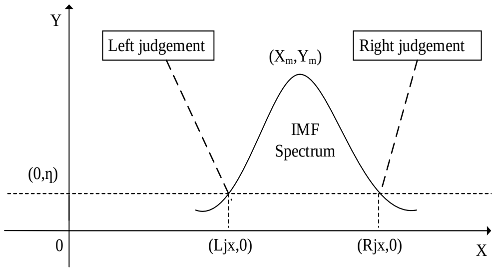

Fig.1 Punctuation selection diagram

(5)Sort K components according to peak-to-peak abscissa X_m of each component as Fig.2.

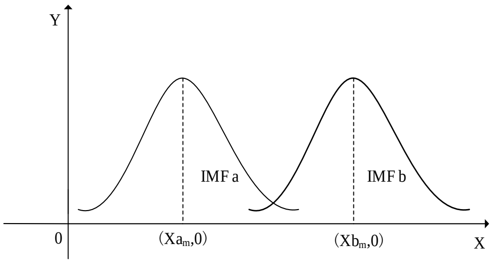

Fig.2 Schematic diagram of component sorting

(6)Subtract the abscissa of the component right punctuation by the horizontal coordinate of the left component of the next component, so as to judge the modal overlap occurs according to the positive or negative difference as Fig.3.

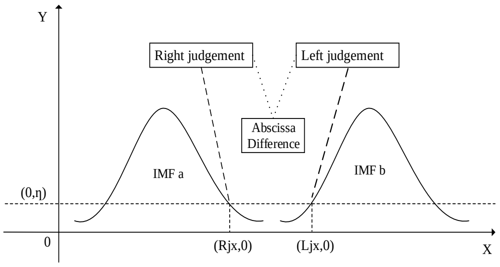

Fig.3 Schematic diagram of overlap decision

In order to ensure that the fault information is enough obvious in each component, the decompose the mode parameter K should be set as large as possible. Based on experiment, K is set from 9 to 1; The value of the quadratic penalty factor α does not need a certain value but a suitable interval from 1000 to 8000. When the constraint rules are satisfied, all modal can be decomposed without overlap.

4 Comparison between G-VMD algorithm and P-VMD algorithm

4.1 Comparison of algorithm flow

The Decomposition process of theses two algorithms is similar. They all use VMD to decompose signal and fault signal is decomposed into multiple IMF components, the fault frequency is found by combining envelope spectrum entropy. But the differences mainly exist in parameters K and α optimization.

In G-VMD algorithm, the genetic algorithm is used to search the optimal combination of parameters K and α of VMD algorithm, the number of times to call VMD algorithm is different according to the definition of maximum genetic algebra and population size. After finding the optimal combination, VMD algorithm is also called again to decompose the signal. In the P-VMD algorithm, VMD algorithm has been invoked two times, the first call and the permutation entropy algorithm are combined to realize the signal denoising process, and the second call realizes the decomposition process of the denoised signal.

4.2 Comparison of running time

The running time of G-VMD algorithm is much longer than that of P-VMD algorithm. When the maximum genetic algebra and population size initialization are larger, the running time of G-VMD algorithm is longer. In general, the larger the maximum genetic algebra and population size initialization are, the more accurate the optimal combination of parameters obtained by genetic algorithm. The reason for the long running time of G-VMD algorithm is that VMD algorithm calls many times in genetic algorithm iterations for searching the optimal parameter combination, while VMD algorithm only calls less times in P-VMD algorithm, which greatly reduces the running time of the program.

4.3 Comparison of the results in bearing fault diagnosis

The inner ring fault signal with shaft speed of 1750r/min and sampling frequency of 12kHz is selected to load into G-VMD algorithm and P-VMD algorithm for signal decomposition, so as to obtain the fault location. It is known that the characteristic frequency of inner ring fault is about 157.5Hz[12]. The time-domain and frequency-domain diagrams of bearing inner ring fault are shown in Fig.4 and Fig.5. Fig.4 shows the signal contains some regular impact components and noise components, and the useful information is not obvious. Fig.5 shows that the signal contains many frequency components.

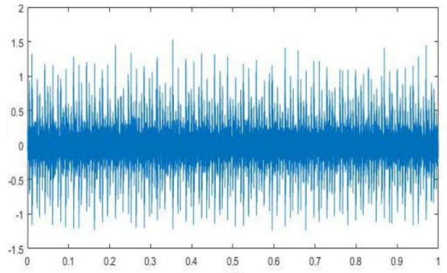

Fig. 4 time domain diagram of bearing inner ring fault signal

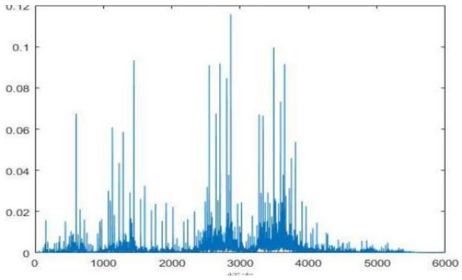

Fig. 5 the spectrum of bearing inner ring fault signal

G-VMD algorithm is used to decompose the fault signal and find the fault location. It can be seen from the Fig.6 that when the genetic evolution algebra is 7, the fitness function value is 27.5, and then with the increase of genetic algebra, the fitness function value will not change. At this time, the best combination of influence parameters [α, k] is [4023, 3]. Set the parameters of VMD algorithm as the best combination of influence parameters [α, k] = [4023, 3], load the vibration signal of test-bed into VMD algorithm for signal decomposition, and obtain three IMF components. The waveform is shown in Fig.7(a) and envelope spectrum of each modal component is shown in Fig.8(a). The envelope spectrum entropy of each IMF component is calculated, as shown in Fig.9(a). By observing the histogram data, it is found that the envelope spectrum entropy of the first component is the smallest, and the corresponding envelope spectrum entropy is 0.1085, which can be considered as the best component containing rich fault feature information. Then, the envelope spectrum is obtained by Hilbert envelope demodulation of IMF1 component, as shown in Fig.9(a). From the envelope spectrum, it can be seen that the fault frequency is 157.5 Hz, which is the same as the known inner ring fault frequency.

P-VMD algorithm is used to decompose the fault signal and find the fault location. The maximum K is the appropriate decomposition levels and the corresponding α is the appropriate quadratic penalty factor. The best combination of influence parameters [α, k] = [3400, 4] is found by the implementation of the algorithm. The vibration signal of the test-bed is loaded into the VMD algorithm for signal decomposition, and four IMF components are obtained. The waveform is shown in Fig.7(b) and envelope spectrum of each modal component is shown in Fig.8(b) and Fig.9(b). From the envelope spectrum, the frequency point of the fault is 157.5 Hz, which is the same as the known inner ring fault frequency.

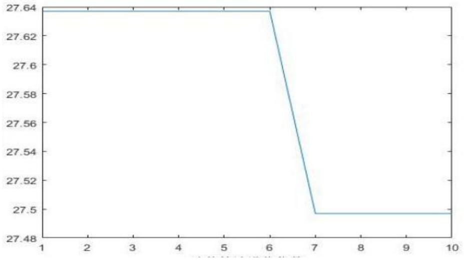

Fig.6 evolution curve of fitness function of genetic algorithm with evolution algebra

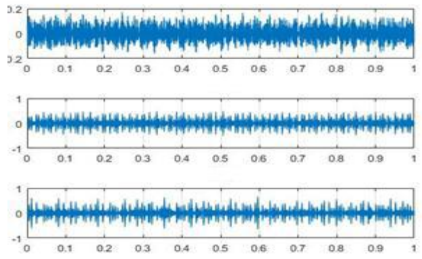

Fig.7(a) Waveform of IMF component decomposed by GVMD

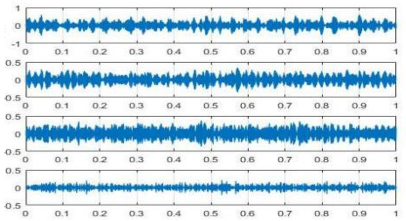

Fig.7(b) Waveform of IMF component decomposed by PVMD

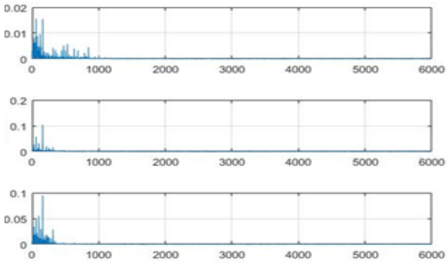

Fig.8(a) envelope spectrum of IMF components decomposed by GVMD

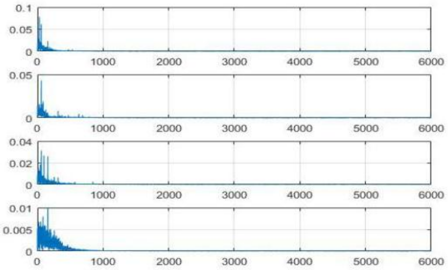

Fig.8(b) envelope spectrum of IMF components decomposed by PVMD

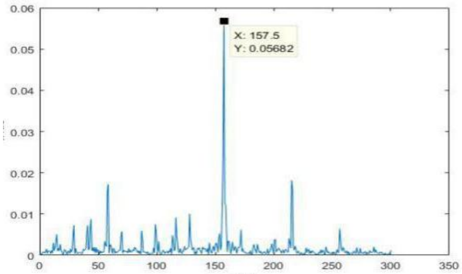

Fig.9(a) Hilbert envelope spectrum of IMF1 component by GVMD

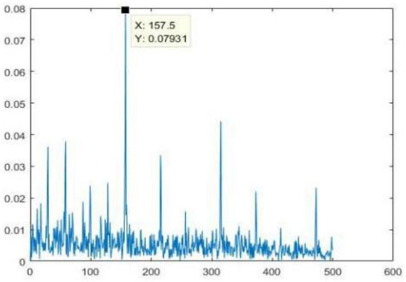

Fig.9(b) Hilbert envelope spectrum of IMF1 component by PVMD

From above, the two optimized VMD algorithms can accurately find the fault frequency point of bearing fault signal. But the whole frequency domain of the envelope spectrum of the best component obtained by P-VMD algorithm is seriously disturbed by noise because its K is larger than that of G-VMD. The results show that the G-VMD algorithm has less noise interference than the P-VMD algorithm.

5. Conclusion

Compared with the running time, P-VMD algorithm can save time greatly, but the parameter K is larger than that of G-VMD. The threshold δ may effect the accuracy and P-VMD can not realized global optimization. While the G-VMD algorithm is combined with genetic algorithm to search for the best parameter combination of K and α, and find the optimal value through multiple iterations of genetic algebra. G-VMD has solid principle on the basis of theory and experiment, the best combination of parameters is more accurate, and the probability of error is very small, but the running time is longer than that of P-VMD.

In a word, these two optimization algorithms have their own advantages. In different actual situations, considering the accurate value of K, α and running time, the suitable algorithm for bearing fault signal diagnosis can greatly improve the efficiency of diagnosis.

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References

[1] Tang Guiji, Wang Xiaolong. Variational mode decomposition method and its application in early fault diagnosis of rolling bearing [J]. Journal of Xi'an Jiaotong University, 2015,49 (5): 73-81.

[2] Dragomiretskiy K, Zosso D. Variational mode decomposition[J]. Signal Processing, IEEE Transactions on,2014, 62(3): 531-544.

[3] Zhang Feng. Application of high frequency envelope spectrum analysis technology in rolling bearing fault diagnosis [J]. China Equipment Engineering, 2012 (11): 53-55.

[4] Dragomiretskiy K, Zosso D. Two-dimensional variational mode decomposition[C]//Energy Minimization Methods in Computer Vision and Pattern Recognition. Springer International Publishing, 2015: 197-208.

[5] Ma Fuqi, Jia Rong, Wu Hua, et al. Application of EMD Based on complex data in fault diagnosis of water guide bearing [J]. Journal of hydropower, 2017, 36 (2): 75-82.

[6] Yang Yu, Yu Dejie, Cheng Junsheng. Fault diagnosis method of rolling bearing based on Hilbert marginal spectrum [J]. Vibration and shock, 2005, 24 (1): 70-72.

[7] Houck C R, Joines J A, Kay M G. A genetic algorithm for function optimization: a Matlab implementation[R]. NCSU－IE Technical Report. Carolina: North Carolina State University,1995.

[8] Bian Jie. Bearing fault diagnosis based on genetic algorithm parameter optimization with variational mode decomposition and 1.5D spectrum [J]. Propulsion technology, 2017,38 (07): 1618 – 1624.

[9]XingYun,RongJian. Featuresmethod for selecting vmd parameters based on spectrum without modal overlap.

page1605(2020)012002. IOP publishing, 2020.

[10] Nocedal, J., Wright, S.J.: Numerical optimization, 2nd edn. Springer, Berlin (2006).

[11] Wang X, Zi Y, He Z. Multiwavelet denoising with improved neighboring coefficients for application on rolling bearing fault diagnosis[J]. Mechanical Systems and Signal Processing, 2011, 25(1): 285-304.

[12] Case western reserve university bearing datacenter [EB/OL]. (2011-05-03). http :// csegroups. case. edu/ bearing datacenter/home.