Application of Sparse Component Analysis-Empirical Mode Decomposition in Compressor Fault Diagnosis

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Abstract. The key of mechanical fault vibration diagnosis is to obtain vibration state information in an all-round way, and the key point is fault signal separation and feature extraction. Early fault signals and weak signals are submerged in strong background noise, which directly affects the effect of signal extraction and brings difficulties to mechanical fault diagnosis. In this paper, a method of mechanical fault vibration diagnosis based on Sparse Component Analysis (SCA) and Empirical Mode Decomposition (EMD) is proposed. Combining the advantages of the two methods, SCA is used to remove interference signals quickly, extract useful signals, and EMD is used to decompose fault feature information efficiently. Compared with other methods, this method can extract complex fault signals and weak symptoms early, comprehensively and accurately, and extract signals with higher similarity and more accurate separation accuracy. It has not only theoretical research value, but also practical engineering significance.

Introduction

Centrifugal compressor is a large rotating machinery widely used in the production of petrochemical industry and other departments. Because of its long-term continuous high-speed rotation, complex equipment structure, it is prone to equipment failure, resulting in equipment paralysis and even huge economic losses and casualties. Vibration is the main fault in production. People pay more and more attention to the vibration of centrifugal compressor. There are many studies on the vibration mechanism, signal analysis, detection and diagnosis methods of centrifugal compressor at home and abroad, and many achievements have been made, which makes the reliability, safety and economy of centrifugal compressor continuously improve. The key problems of mechanical fault vibration diagnosis technology are signal acquisition and feature extraction. There are many methods for vibration signal processing, which can be roughly divided into two categories: one is the traditional method, the typical one is amplitude domain analysis, Fourier transform and correlation analysis. The other is modern methods, such as Wigner-Ville distribution, spectral analysis, wavelet analysis, blind source separation, empirical mode decomposition, sparse decomposition and high-order statistics analysis. Among them, wavelet analysis, blind source separation, Hilbert-Huang transform and sparse decomposition have good effects on unbalanced signals, so they are widely used.

In order to get more accurate, practical and advanced methods, researchers at home and abroad have improved and developed different methods. Especially, by combining several methods, Yang Chang avoids shortcomings and realizes better the analysis of unbalanced signals. In the process of continuous exploration, the theory is proved to be feasible, and gratifying results have been achieved. For example, Zhang Hao of Xi’an Jiaotong University combines sparse decomposition with wavelet transform. Dr. Zhu Wenlong of Huazhong University of Science and Technology combines independent component analysis with empirical mode decomposition in vibration diagnosis technology, and successfully provides some new signal extraction methods. However, there are few applications of sparse analysis theory and empirical mode decomposition to mechanical fault diagnosis at home and abroad. Therefore, based on sparse component analysis theory and empirical
mode decomposition, vibration diagnosis technology for mechanical faults is studied. SCA is used to remove interference noise, get effective information, EMD is used to decompose the signal, and accurately separate and recognize the signal. It is also a hot research direction in the future. It has high theoretical research value and good practical popularization. Meaning, it also provides reference for vibration signal extraction method of mechanical fault.

**Basic Theory of Sparse Decomposition**

Sparse component analysis (SCA) was proposed by CHEN in 1990s. Because of the complexity of the algorithm, a large number of scholars have devoted themselves to reducing the complexity of the algorithm or designing faster and simpler algorithms. Among them, greedy tracking algorithm mainly includes matching pursuit (MP) algorithm, which was proposed by Mallat and Zhang in 1993. The algorithm approximates the decomposed signal step by step according to the iteration fraction. MP algorithm is simple in principle, but it needs a lot of calculation. Following MP algorithm, orthogonal matching pursuit (OMP), sectional OMP (StOMP) and regularized OMP (ROMP) arithmetic have emerged. Researchers have also introduced intelligent optimization algorithms, such as ant colony optimization, particle swarm optimization (PSO) and genetic algorithm, into the optimal atomic search process of matching pursuit, which speeds up the search, reduces the memory and computational load, and obtains them. Very good results.

Another classical sparse decomposition algorithm is convex relaxation method, which is mainly BP algorithm. This algorithm was proposed by D. Donoho et al. in 1999. Its core idea is to use L1 norm instead of L0 norm to solve the objective function. The convex optimization problem in sparse decomposition is simplified to a linear programming problem, which avoids MP problem and reduces the computational difficulty. There are many algorithms that are in line with the idea of BP algorithm: interior point method, gradient projection method, iterative threshold method, SLO range method and Focuss algorithm.

Sparse decomposition theory has attracted the attention of a large number of researchers at home and abroad as soon as it was proposed. It has been widely used in engineering practice, such as signal compression coding, image denoising and image compression. It involves many fields such as radar, power system, medicine, earthquake, mechanical vibration and so on. However, one of the most influential applications of sparse decomposition theory is E. Candes, Tao and Romberg. And the Compressive Sensing (CS) theory proposed by D. Donoho in 2006. The premise of CS theory is that the signal is sparse or compressible. The sparse representation of the signal can effectively characterize the essential characteristics of mechanical fault signal. Moreover, the theory breaks the limitation of sampling frequency in Nyquist sampling theorem, making the sampling frequency of the signal lower than that of Nyquist, and provides a new way for signal sampling. Some scholars have proposed that analog information should be used for signal sampling. The converter takes the place of the traditional AD converter to sample the signal. Rice University has developed a single-pixel camera, which can use fewer photosensitive elements to obtain much fewer point recovery images than those captured by traditional CCD and CMOS imaging devices. With the further development and application of CS theory, the sparse decomposition theory will reach its climax.

**Empirical Mode Decomposition**

Empirical mode decomposition (EMD) was proposed by Huang N E of NASA in 1998. It has adaptive decomposition and excellent local analysis ability. The IMF obtained from EMD decomposition of mechanical vibration signals can be regarded as the component signals in different frequency ranges of the original signals. Combining with the relevant information of monitoring objects, the appropriate IMF is selected to reconstruct the source signals. It gives the definition of IMF for the first time, allows the amplitude of IMF to change, breaks through the limitation of traditional definition of simple harmonic signal with invariant amplitude as basic signal, makes signal analysis
and algorithm more flexible and convenient; it is a more adaptive time-frequency localization analysis method. Firstly, the original signal is decomposed into a set of intrinsic mode functions (IMF), and then the time spectrum of the signal is obtained by Hilbert transform (HT) for each intrinsic mode function. EMD is a data-based signal analysis method, which does not require prior knowledge of the signal. Moreover, the basis function of the decomposition process is obtained from the adaptive decomposition of the original signal. Therefore, it overcomes the shortcomings of traditional spectral analysis methods such as linearity, stationarity and non-adaptive of wavelet transform. EMD has obvious advantages, it can accurately make time-frequency maps, which is difficult to achieve in other signal analysis such as wavelet. Therefore, this method has been widely used in fault diagnosis, seismic monitoring and other fields, and has achieved good results.

**Deficiencies of Sparse Decomposition (SCA) and Empirical Mode Decomposition (EMD)**

SCA has more advantages than traditional signal decomposition. Under the effect of sparse decomposition algorithm, a series of atoms matching the signal characteristic information are adaptively selected from the redundant atomic library (over-complete dictionary). The signals to be decomposed are expressed as linear superposition of these atoms. The atoms in the over-complete dictionary have good time-frequency characteristics, so they can represent any kind of signal in practice. Because the dictionary is highly redundant, when decomposing the actual complex signal, the characteristic information of the signal will not be dispersed to many atoms, that is, the redundancy ensures a certain sparsity, so as to ensure that these characteristic components represent the original signal with high accuracy, thus obtaining a very concise expression of the original signal, that is, sparse representation. SCA captures the main components reflecting signal characteristics with a small number of representation coefficients, which is concise and easy to store data. In the field of image compression and noise reduction, many achievements have been made, but it is just beginning to be used in fault diagnosis because of the large amount of computational work. SCA also has some shortcomings, such as what kind of atoms to choose to construct a suitable dictionary and cascade dictionary family, and how to improve the convergence of the algorithm when the algorithm is too complex.

The basic theory of EMD is to assume that any signal is composed of some different inherent modes, each of which can be linear or non-linear. If the modes are superimposed on each other, a composite signal will be formed. IMF has only a single frequency component at each moment, thus the instantaneous frequency has physical significance. EMD method is the process of "screening" complex signals, decomposing the signals step by step, and obtaining a series of IMFs with different characteristic scales. Then the instantaneous frequency of each IMF is obtained by Hilbert transform, and the Hilbert spectrum and marginal spectrum are obtained. Hilbert spectrum accurately describes the variation of signal amplitude with time and frequency in the whole frequency band. Marginal spectrum indicates the distribution of amplitude and energy in the unit frequency, which represents the accumulation of probability distribution of amplitude in the whole data band. However, there are some shortcomings, such as: EMD produces some unrelated IMFs in low frequency band, which may cause the results to be incomprehensible; the first IMF may include too wide frequency band to obtain single frequency components; it cannot separate low-energy signal components; when strong noise is mixed in the characteristic signal, it cannot obtain satisfactory intrinsic mode functions, etc.

Therefore, based on sparse component analysis theory and empirical mode decomposition, vibration diagnosis technology for mechanical faults is studied. SCA is used to remove interference noise, get effective information, EMD is used to decompose the signal, and accurately separate and recognize the signal. It is also a hot research direction in the future. It has high theoretical research value and good practical popularization. Meaning, it also provides reference for vibration signal extraction method of mechanical fault.
Feasibility and Realizability of Combining SCA with EMD

In order to better extract fault feature signals and restore the source signals causing the fault, considering the advantages of SCA and EMD in feature extraction, a new feature extraction method based on SCA and EMD is proposed, which combines the two methods to make up for their shortcomings. The specific implementation steps of this method are as follows:

Step 1: Judge chaos. The learning parameters are initialized randomly and the Lyapunov number is calculated to determine whether the algorithm is chaotic. If the Lyapunov exponent is positive, the algorithm is chaotic and the learning parameters are adjusted until convergence.

Step 2: Separate the multi-channel vibration signals with SCA, and get the independent statistical components of energy, which is necessary for EMD decomposition.

Step 3: Autocorrelation analysis. The influence of environmental noise $n(t)$ is removed by each statistical independent component.

Step 4: EMD decomposition, using EMD to decompose all statistical independent components separately, get component eigenmode function;

Step 5: Cofrequency reconstruction. The eigenmode functions of the original signal are obtained by accumulating the intrinsic eigenmode functions $m$ of the same frequency of each statistical independent component and preserving all the $m$ of different frequencies.

Step 6: Extract fault characteristic signal. The eigenmode functions of the original signals can be used to find out the characteristic signals which can characterize the faults of generating units, such as 1-fold, multi-fold, 50HZ, 1/6-1/2-fold and so on.

Examples Verification

There are some abnormalities in the work of an EI370-9/0.97 centrifugal compressor in Longyan Chemical Plant. Especially when the running speed is twice the critical speed, the vibration increases sharply, accompanied by abnormal sound of "tap and tap". The designed working speed is 8886 r/min, the first critical speed is 3010 r/min, the double critical speed is 11200 r/min, and the rotor support bearing uses cylindrical bush bearing, and the tile top clearance is 0.20 mm. The lateral clearance was 0.10 mm.

SCA is used to optimize the objective function and solve the sparse representation model. The sparse representation coefficients of transient components on the base are obtained. EMD is used to reconstruct the signal for analysis, and the fault characteristic frequencies can be accurately extracted. Specific experiments are not described in detail. Fig. 1, the fault characteristic frequency extracted by this method is 49 Hz, which is in good agreement with the measured value of 50 Hz. It is close to the first-order critical frequency $f_1=3010/60=50.2$ Hz of the rotor. The peak value exceeds the peak value of the fundamental frequency vibration, and the axis trajectory diffuses irregularly, which accords with the basic characteristics of oil film oscillation. To this end: first, increase oil temperature, when oil film oscillation occurs, increase oil temperature from 35 degrees Celsius to 42 degrees, reduce oil viscosity, which is conducive to Journal stability; second, change the cylindrical bush of the original compressor rotor support Bush to elliptical dislocation bush, change the Bush top clearance from 0.2 mm to 0.17 mm; third, increase the center of the two supporting bushes of the rotor by 0.15 mm, and increase eccentricity. After six months of operation, no oil film oscillation occurred, the vibration values were less than 0.2 mm, and no noise occurred.
Summary
Aiming at the complex and special characteristics of mechanical fault signals and combining the advantages of two modern signal decomposition methods, a new method of signal extraction based on SCA and EMD is proposed. It has been proved by modeling, calculation, simulation and experimental verification that the theory is reliable, the method is feasible, easy to popularize and widely used, thus promoting the development of mechanical fault vibration diagnosis technology. Compared with other algorithms, this method can extract complex fault signals and weak symptoms early, comprehensively and accurately, and extract signals with higher similarity and more accurate separation accuracy. The extraction performance of this method is better, and it can meet the actual needs of engineering.

References