Feature extraction of non-linearity and low noise-signal ratio signals and its application to engine fault diagnosis

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Abstract. Since the vibration signals of engine cylinder head come from different interference sources, it is difficult to detect weak but useful signals in the background of noise. Aiming at nonlinear and low noise characteristics of engine vibration signals, a method based on integrated empirical mode decomposition (EMD) and fractal dimension is proposed. Firstly, the integrated EMD method is used to decompose the nonlinear low noise signal into a set of intrinsic mode functions from high to low. Then the morphological fractal dimension is applied to the intrinsic mode function (IMFs). The fractal dimension of the characteristic IMF is calculated. The vibration signals of a diesel engine exhaust valve under normal and leakage conditions are analysed. The results show that this method can extract fault features of diesel engine exhaust valve.

1. Introduction

Traditional vibration signal processing techniques, including time-domain and frequency-domain analysis, are based on the assumption that the signal generation process is linear and stable. In view of the non-stationary and non-linear of vibration signal, several advanced signal analysis technologies are introduced and applied to the fault diagnosis of machinery, such as engine [1]. Because engine has many and complex moving parts, many excitation sources and wide frequency range, all kinds of excitation are reflected in its surface vibration through corresponding transmission and coupling, combined with the integration of noise, the engine vibration signal is extremely complex, and when engine is in different states, due to the influence of nonlinear factors such as clearance, dynamic load, contact force, stiffness, etc. The unified society presents complex nonlinear behavior. It is difficult to analyse the geometry of the vibration signal of the engine by using the time-frequency analysis method.

Fractal geometry provides a geometric structure analysis method for complex signals, and the development of fractal geometry theory provides a new idea for diesel engine fault diagnosis [2]. Fractal dimension is an important parameter used to quantitatively describe the behavior of nonlinear system in state space. At present, many fractal dimensions have been proposed, such as Hausdorff dimension, correlation dimension and box dimension. The fractal dimension is based on the basic idea of measuring the fractal set in different scales, that is, the set of irregular geometry to describe the complexity of the signal, which is consistent with the idea of measuring the geometric shape of the
analysed object in different scales by multi-scale morphology. In order to study the method of estimating signal fractal dimension by using multi-scale morphological operator, Maragos. P proposed to estimate signal fractal dimension by using morphological filter operator [3]. The fractal dimension algorithm based on morphology has the advantages of low computational complexity, good stability of calculation results, sensitivity to the change of signal geometry, and is not affected by signal amplitude range and other factors [3-5].

Since most of the vibration signals detected in practical engineering contain noise, the noise component has a great influence on the calculation of fractal dimension. In order to get the fractal dimension of shape, it is necessary to denoise the vibration signal. Integrated empirical mode decomposition (EMD) can adaptively decompose the nonlinear and non-stationary signals into the sum of the finite basic mode components (IMF) according to the local time characteristic scale of the signal, without preselecting the basis function [6]. In this paper, multi-scale fractal dimension and integrated EMD are introduced into vibration signal analysis.

2. New method

2.1. Morphological fractal dimension

Morphology is a mathematical method developed on the basis of set theory, integral geometry and topology. Erosion and swelling are two basic operations of mathematical morphology. This coverage can be obtained by using functional structural elements of one-dimensional corrosion and swelling, defined as,

\[
G_m = \Theta(f_n - g_m) \quad (1)
\]

\[
G_m = \oplus(f_n - g_m) \quad (2)
\]

Hence, for one-dimensional discretetime signal \( f(n), n = 0,1,\ldots,N \), the structuring element is defined at scales \( \varepsilon \) [3],

\[
\varepsilon g(n) = g \oplus g \oplus \cdots \oplus g \quad \varepsilon \text{TIMES} \quad (3)
\]

Taking \( \varepsilon = 1, 2, \cdots, \varepsilon_{\text{max}} \) as the range of analysis scale, \( \varepsilon_{\text{max}} \leq N / 2 \), then the results of erosions and dilations of the signal \( f(n) \) at different scales \( \varepsilon \) are \( f \Theta \varepsilon g(n) \) and \( f \oplus \varepsilon g(n) \) respectively.

The cover area of the signal at the scale \( \varepsilon \) is defined,

\[
A_g(\varepsilon) = \sum_{n=1}^{N} (f \oplus \varepsilon g(n) - f \Theta \varepsilon g(n)) \quad (4)
\]

According to [3], \( A_g(\varepsilon) \) satisfies the following conditions,

\[
\log \frac{A_g(\varepsilon)}{\varepsilon^D} = D_M \log \frac{1}{\varepsilon} + c \quad (5)
\]

where \( \varepsilon = 1, 2, \cdots, \varepsilon_{\text{max}} \).

The Minkowski-Bouligand dimension \( D_M \) of the signal is defined as,
According to the analysis of literature [4], we use the flat structure unit with length of 3 as the unit structure unit. Using flat structure element, the estimation result of fractal dimension is not affected by the range of signal amplitude, and the amount of calculation is reduced. According to the method of determining the maximum grid scale of periodic signal, combined with the working cycle characteristics of engine vibration signal, the maximum scale is 60.

2.2. Integrated empirical mode decomposition

Empirical mode decomposition (EMD) can decompose any time-varying signals into finite intrinsic mode components (IMFs). The IMFs represent the natural oscillatory mode embedded in the signal and work as the basis functions. However, one of the major drawbacks of EMD is the mode mixing problem. To overcome the problem, integrated EMD is proposed, which is a noise-assisted data analysis method and defines the true IMF components as the mean of an integrated trials [7]. The procedures can be given as follows.

(1) The time series $N(t)$ of white noise is added to the signal $y(t)$.

$$ S(t) = y(t) + N(t) $$

(7)

(2) The data series $S(t)$ is decomposed into finite IMFs.

$$ S(t) = \sum_{j=1}^{n} c_j(t) + r_n(t) $$

(8)

(3) Repeat steps 1 and 2, but use different white noise series each step, $i = 1 \sim m$.

$$ S_i(t) = y(t) + N_i(t) $$

(9)

$$ S_i(t) = \sum_{j=1}^{n} c_{i,j}(t) + r_{in}(t) $$

(10)

(4) The average value of IMF is obtained and considered as the final decomposition result.

$$ c_j(t) = \frac{1}{m} \sum_{i=1}^{m} c_{i,j}(t) $$

(11)

3. Simulation analysis

In order to verify the effectiveness of integrated EMD decomposition, EMD and integrated EMD are used to decompose the simulation signal, which is composed of low-frequency sine and small impact components. Figure 1 shows the time-domain waveform of the simulation signal. Figure 2 shows the decomposition results of EMD. Due to the abnormal interference of noise, EMD produces mode mixing, which leads to the pseudo IMFs, and cannot meet the requirements of feature extraction. The sinusoidal signal and impulse signal are decomposed into IMF component C1, and then the sinusoidal signal is decomposed into IMF component C1 and C2. The decomposition result has serious distortion, and the EMD generation mode mixing, so the pseudo IMF cannot meet the requirements of feature extraction.

The simulation signal is decomposed by integrated EMD, the average decomposition times is 100, and the noise amplitude is 0.01 times of the signal standard deviation. As shown in Figure 3, C1 component corresponds to impulse signal component, C2 component corresponds to sinusoidal signal, and small impulse component and sinusoidal signal are decomposed accurately.
4. Experimental analysis

A four cylinder four stroke diesel engine is under the condition of normal working condition and different degree of exhaust valve leakage. The vibration response signals of diesel engine on the same cylinder surface are measured, which represent that the engine is in normal, slight and serious leakage state respectively. The sampling frequency is 25.6 kHz. The crankshaft speed of diesel engine is 1100r/min, and the vibration signal of diesel engine exhaust valve under three working conditions is shown in Figure 4. The fractal dimension of vibration signal is calculated directly by the fractal dimension estimation algorithm based on morphology, as shown in Figure 5. The fractal dimension is very close, so it is difficult to distinguish the state of exhaust valve.

By integrated EMD, the vibration response of diesel engine can be divided into several IMF, which represent the high frequency component to the low frequency component of the original vibration signal. In the leakage fault of exhaust valve, the inherent vibration component contains fault information, which belongs to high frequency component. Therefore, by calculating the fractal dimension of imf1, the working state of exhaust valve can be quantified. As shown in Figure 6, the fractal dimension can be clearly separated from the three regional conditions of diesel engine exhaust valve leakage.
Figure 4. Vibration signals of diesel engine in three conditions

Figure 5. Morphological fractal dimensions of vibration signal in three conditions
5. Conclusion
Through analysis of fractal dimension of measured vibration signals of diesel engine, it is verified that the noise component will greatly affect the calculation result of the fractal dimension of the measured vibration signal. Therefore, it is not reliable to directly calculate the fractal dimension of the measured vibration signal of diesel engine to describe the working state of diesel engine, so it is very necessary to denoise the vibration test signal. The integrated EMD method can effectively separate the characteristic components of the measured non-linear non-stationary vibration signal from the noise and other interference components, thus improving the signal-to-noise ratio of the signal fractal analysis. The IMF component with fault features is analyzed by morphological fractal dimension, which can quantitatively describe the geometric characteristics of the vibration response signals of diesel engine, and the different working states of diesel engine are clearly distinguished. It is feasible to use morphological fractal dimension of the IMF component containing fault feature as the feature to judge the working state and fault identification of air valve leakage.

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References
[1] Z. Geng, J. Chen, J. B. Hull 2003 *International Journal of Mechanical Sciences*, vol 45 p 1391
[2] B. B. Mandelbrot 1982 *The fractal geometry of nature*, (New York: Freeman).
[3] P. Maragos, FK Sun 1993 *IEEE Transactions On Signal Processing*, vol41 p 108.
[4] P Maragos. E 1989 *Transactions on Pattern Analysis and Machine Intelligence*.vol11 p 701
[5] P Maragos 1987 *IEEE International Conference on ICASSP*, Dallas, p. 241.
[6] Z H Wu, NEHuang 2009 *Advances in Adaptive Data Analysis* vol 11 p 1.