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Study on Performance of Remanufactured Engine Based on EMD

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Abstract

According to the non-stationary property of vibration signal, the vibration signal is decomposed by empirical mode decomposition (EMD). And this method is applied to study the remanufacturing level of engine. Based on the decomposition of vibration signal, correlation coefficient is introduced to study the correlation between IMF (Intrinsic Mode Function) components and original signal, and dynamic structure of IMF components is analyzed by correlation dimension. In order to study the remanufacturing level of engine, correlation coefficient and correlation dimension are considered in the function of IMF, and an index of vibration intensity is proposed. A corresponding relationship is established between remanufacturing level and vibration intensity. This method has been proved that the running state of engine can be reflected by vibration intensity, and this index can be used to evaluate the remanufacturing level of engine.

***Keywords**: Power engineering and engineering thermophysics, EMD, vibration intensity, remanufactured engine, correlation coefficient, correlation dimension*

1. Introduction

In the study on the running state of engine, a lot of information is hidden in vibration signal, which has been widely used in engine research [1, 2]. Currently, there are many vibration signal analysis and processing methods, including short-time Fourier analysis, wavelets analysis and so on, but these methods have great limitations in the treatment of non-stationary signals [3, 4], EMD (Empirical Mode Decomposition) is based on the local characteristic time scale of signal and decompose the complicated signal into a number of Intrinsic Mode Functions (IMFs), which reflect the real physical information contained in signal.

Remanufactured engine has a huge advantage in energy-saving, environmental protection, resource recycling and other aspects, and has been got the world attention [5, 6, 7]. However, because of the complex structure, numerous moving parts, the complexity of manufacturing, and instability quality of remanufactured parts, the performance of remanufactured engine is difficult to be guaranteed. How to evaluate the remanufactured engine performance is an important research content. Vibration signal and EMD decomposition method are combined to study the remanufactured engine performance, and the correlation coefficient and correlation dimension are introduced into the study. An evaluation index of vibration situation is put forward and is already applied in remanufactured engine research.

2. EMD Decomposition

The Empirical Mode Decomposition (EMD) proposed by Huang in 1998 is a very powerful signal analysis tool for both linear and nonlinear cases [8], its essence is to obtain the intrinsic fluctuation patterns through the characteristic time scale of data, then decompose the data, find the Intrinsic Mode Function (IMFs). The basic steps of EMD decomposition process is as follows [9].

(1) Find all the local extreme points of the signal x(t), and then use the three spline interpolation to connect all of the local maxima and local minima, forming the upper and lower envelopes.

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(2) Calculate the mean of the upper and lower envelopes, denoted as $m_1(t)$, the original data $x(t)$ minus $m_1(t)$, $h_1(t)$ is obtained

$$h_1(t) = x(t) - m_1(t) \tag{1}$$

If $h_1(t)$ is an IMF, then it is the first IMF of the signal $x(t)$.

(3) If $h_1(t)$ is not an IMF, then use $h_1(t)$ as the original data, repeated ①, ②, get the average of the envelopes , denoted as $m_{11}(t)$, $h_{11}(t)$ is obtained

$$h_{11}(t) = h_1(t) - m_{11}(t). \tag{2}$$

And decide whether the result to meet the IMF condition, if not meet, then repeat the cycle, until $h_{1k}(t)$ is a IMF, i.e.

$$h_{1k}(t) = h_{1k-1}(t) - m_{1k}(t). \tag{3}$$

Denote $c_1(t) = h_{1k}(t)$, then $c_1(t)$ is called the first order IMF of signal $x(t)$.

(4) Isolate $c_1(t)$ from $x(t)$, then get

$$r_1(t) = x(t) - c_1(t) \tag{4}$$

Make $r_1(t)$ as the original data, repeat steps ①, ② and ③, get the second component $c_2(t)$ of $x(t)$ that meets the IMF condition, repeat n times, get n components of signal $x(t)$ that meet the IMF condition. So there is

$$\begin{cases} r_2(t) = r_1(t) - c_2(t) \\ r_n(t) = r_{n-1}(t) - c_n(t) \end{cases} \tag{5}$$

When $r_n(t)$ is a monotone function and IMF component can't be extracted from it, the cycle ends. A signal $x(t)$ is decomposed into the sum of n basic model component $c(t)$ and a residual $r_n(t)$, that is

$$x(t) = \sum_{j=1}^{n} c_j(t) + r_n(t) \tag{6}$$

3. Correlation Coefficient

How to analyze the retention degree of the original information in each IMF, In other words, how to get the correlation degree of IMF component and the original signal, is an important problem. In this paper, correlation coefficient is introduced to study the correlation between the characterization of IMF components and the original signal.

In the decomposition process of EMD, due to the influence of the difference error of local calculation value method and boundary effect, the correlation between different components and original data will be different.

Define the correlation coefficient of each IMF component and the original signal as follows [10]

$$\rho_i = \left| \frac{E[(C_i(t) - \mu_i)(S(t) - \mu)]}{\sigma_i \sigma} \right| \tag{7}$$

Where, μ_i —average of component $C_i(t)$;

μ —average of component $S(t)$;
σ_i—standard deviation of component $C_i(t)$;
σ—standard deviation of component $S(t)$。
As,

$$\sigma_i^2 = E\left[(C_i(t)-\mu_i)^2\right].$$

$$\sigma^2 = E\left[(S(t)-\mu)^2\right].$$

Based on Cauchy-Schwarz inequality, we can get

$$\begin{aligned} &E\left[(C_i(t)-\mu_i)(S-\mu)\right]^2 \\ &\le E\left[(C_i(t)-\mu_i)^2\right] * E\left[(S(t)-\mu)^2\right] \\ &\le \sigma_i^2\sigma^2 \end{aligned} \tag{8}$$

Therefore, $0 \le \rho \le 1$.

4. The Correlation Dimension and Vibration Intensity

4.1. Correlation Dimension

Let $\{x_i\}$, i =1, 2, 3, …, n, is the signal time sequences based on the sampling interval T, embedded x_i into the m dimensions Euclidean space R_m, a vector set is got: $\{J(X_{i,m})\}$, i =1, 2, 3, …, L, this process is called space reconstruction, the element denoted as $X_{i,m}=(x_i, x_{i+\tau}, \ldots, x_{i+(m-1)\tau})^T$, i =1, 2, 3, …, L. Among them, $L= N-(m-1)\tau$, τ is the delay time, m is the embedding dimension. Select a reference vector $X_{i,m}$ from the L vectors, and calculate the distance between the remaining L–1 vectors and $X_{i,m}$

$$r_{ij} = d(X_{im}, X_{jm}) = \left|X_{im} - X_{jm}\right| \tag{9}$$

Repeat this process for all vector $X_{i,,}$, and get the correlation function

$$C_m(r) = \frac{1}{L^2}\sum_i\sum_j H\left(r - \left|X_{i,m} - X_{j,m}\right|\right) \tag{10}$$

i,j =1, 2, 3, …, L

Where, r is the scale of phase space after reconstruction, $H(s)$ is the Heavside function, which is defined as

$$H(s) = \begin{cases} 1, s \ge 0 \\ 0, s < 0 \end{cases} \tag{11}$$

The correlation dimension is defined as

$$D = \lim_{r\to 0}\frac{\ln C(r)}{\ln r} \tag{12}$$

4.2. Vibration Intensity

The vibration intensity usually contains three physical quantities: displacement, velocity and acceleration, the general vibration signal contains information about the vibration intensity. After the vibration signal being decomposed by EMD method, the vibration intensity is decomposed into IMF components. In order to study the vibration characteristics of remanufactured engine, a vibration intensity index is proposed through the combination of correlation coefficient and correlation dimension.

The correlation dimension reflects the dynamic structure of IMF components, and the correlation coefficient indicates the correlation between each IMF component and the original data (i.e. contribution ratio of IMF components for the original data). Calculate the root mean square value

$$Ld = \sqrt{\frac{1}{k}\sum_{i=1}^{k}\rho_i D_i} \tag{13}$$

Where,

Ld—vibration intensity;

D_i—correlation dimension of each IMF component;

ρ_i—Correlation coefficient of each IMF component;

k—number of IMF component。

The vibration intensity reflects the vibration characteristics of remanufactured engine, and can be used to study the remanufactured level.

5. Experimental Research

A type of engine crankshaft has been remanufactured. Vibration signals of 4 speeds are got through bench test. During the test, the engine speed are respectively 800, 1000, 1300 and 1800r/min, and the sampling frequency is 12800Hz, the sampling points are 8192. In order to make the research comparability, an engine with good performance is also made bench test, and the vibration signals are got at three speed 800, 1300 and 1800r/min. The sampling frequency and the points are the same as remanufactured engine.

The vibration signal at speed 800r/min and results of EMD decomposition of remanufactured engine are shown on Fig.1. After the EMD decomposition, 11 IMF components and a residual error $r_n(t)$ are obtained. As can be seen from the figure, each IMF component contains different time scales, so that the signal characteristics revealed in different resolutions. In fact, the EMD method is similar to a principal component extraction method, the original signal information in contained in the IMF components of decomposition results.

Vibration signals are decomposed by EMD, and the correlation coefficient of the IMF components is calculated. The results are shown in table 1. The IMF correlation coefficient of signal 1~4 is remanufactured engine, and the IMF correlation coefficient of signal 5~7 is normal state of the engine (not manufactured). As can be seen from the table, correlation coefficient of signal 1~4 each is gradually decreasing, and correlation coefficient of signal 5~7 is different, the values are concentrated on 0.1 or so. It is shown that the vibration state of manufactured engine has changed due to the manufactured error. This change is contained in the IMF components through EMD decomposition. There is little contribution of IMF components decomposed from normal engine for original signal. This also shows the stability of vibration state of normal engine.

Based on the EMD decomposition, the correlation dimension of each signal and IMF components is got, the results are shown in table 2. As can be seen from the table, the correlation dimension of signals are greater than 2 and less than 3 except signal 4, and there is not obvious difference between remanufactured engine and normal ones. Similar with the correlation coefficient, the IMF component correlation dimension of signal 1~4 is decreased, and the IMF component correlation dimension of signal 5~7 decreases firstly and then increases gradually.

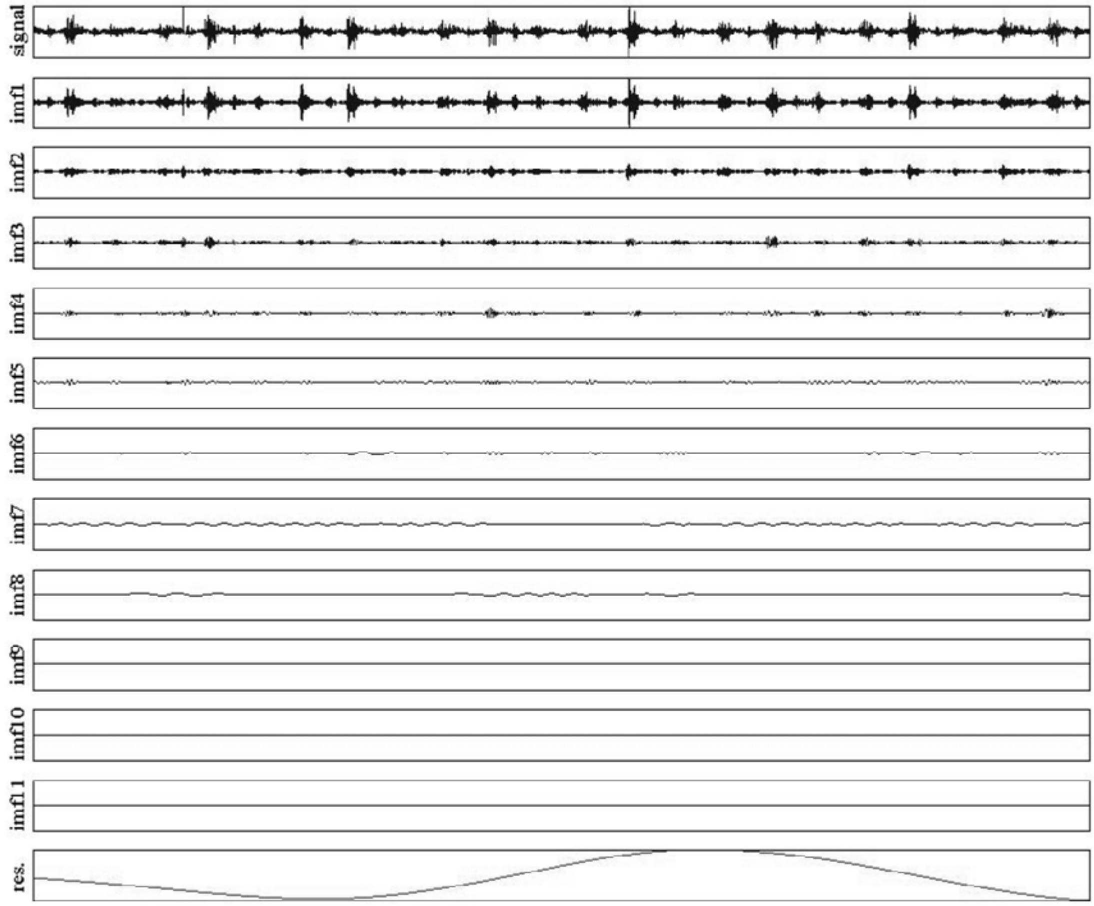

Figure 1. The result of EMD for vibration signal

Table 1. The result of correlation coefficient

	IMF1	IMF2	IMF3	IMF4	IMF5	IMF6	IMF7	IMF8	IMF9	IMF10	IMF11
Signal 1	0.6454	0.6709	0.6087	0.5751	0.5684	0.6012	0.6093	0.5738	0.4833	0.4009	0.3921
signal 2	0.8127	0.7749	0.7739	0.7483	0.7776	0.7225	0.7794	0.6585	0.4911	0.2777	0.6401
signal 3	0.1666	0.1754	0.1354	0.2092	0.1759	0.2108	0.2091	0.2424	0.1724	0.3791	0.3918
signal 4	0.5174	0.4707	0.4362	0.4490	0.3767	0.4273	0.4175	0.4528	0.3791	0.3908	0.3204
signal 5	0.1638	0.0580	0.0332	0.1580	0.1372	0.1721	0.0855	0.1149	0.1306	0.0984	0.1303
signal 6	0.0497	0.0399	0.0662	0.0523	0.0851	0.0999	0.0793	0.0839	0.1096	0.0914	0.1025
signal 7	0.1099	0.0880	0.0884	0.0828	0.1367	0.0747	0.0511	0.0937	0.15117	0.1402	0.1340

In order to study the remanufactured level of remanufactured engine, the vibration intensity of each vibration signal are calculated using correlation coefficient and correlation dimension, the results are shown in table 3. As can be seen from the table, the values of vibration intensity of remanufactured engine are more than 0.5. Three values are greater than or close to 1 among the values of four vibration signal intensity. The values of three normal engine are at about 0.3, and the maximum is not more than 0.4. So the remanufactured level of manufactured engine is quantified. For the vibration intensity, the smaller, the better. The best manufacture level is at around 0.4. With the increase of values, the remanufactured level gradually decreased.

In the study of fault diagnosis on mechanical equipment, many researchers introduced the concept of healthy to the study of machine running state [11,12,13]. Based on this idea, take the vibration intensity as the evaluation index of remanufactured level. We can Judge the remanufactured level of engine according to the mean value of vibration intensity under various conditions. And the remanufactured level can be divided into five grades: very good, good, little poor, poor, terrible, as shown in Table 4.

Table 2. The result of correlation dimension

	vibration signal	IMF1	IMF2	IMF3	IMF4	IMF5	IMF6	IMF7	IMF8	IMF9	IMF10	IMF11
signal 1	2.5390	3.2474	3.6761	3.1656	2.0782	2.0355	1.2118	1.4292	0.9122	0.3443	0.0946	0
signal 2	2.4640	3.2025	3.6333	3.1439	2.1205	1.4724	1.4946	1.4563	0.5054	0.1952	0.0381	0
signal 3	2.1301	2.3288	3.5301	3.0642	1.8027	2.2442	1.6866	1.3505	0.9214	0.5702	0.3128	0.0165
signal 4	0.8500	1.0114	2.8222	3.2757	2.8031	3.1384	2.5015	2.0467	1.7184	1.6129	1.2648	0.4624
signal 5	2.2909	3.9015	2.9467	2.1736	1.1104	0.4607	0.4908	0.5106	0.4059	1.2913	1.2552	1.2504
signal 6	2.3359	3.8281	2.9321	2.0801	0.9588	0.7305	0.2675	0.6606	0.6477	1.6646	1.6544	1.4274
signal 7	2.0718	3.8667	3.1518	1.9432	1.1464	0.5405	0.6345	0.3819	0.6991	0.5352	0.9393	1.1555

Table 3. The vibration intensity of vibration signal

	signal 1	signal 2	signal 3	signal 4	signal 5	signal 6	signal 7
Ld	1.0076	1.0970	0.5459	0.9379	0.3989	0.3262	0.3745

The mean value of remanufactured engine ahead is 0.8971, contrast to table 4, the remanufactured level is good, but the value of vibration intensity is close to the edge of the little poor, its remanufactured level can improve further.

Table 4. The corresponding relationship between remanufacturing level and vibration intensity

vibration intensity value Ld	Engine remanufacturing level
Ld≤0.5	Very good
0.5≤Ld≤1.0	Good
1.0<Ld≤1.5	Little poor
1.5<Ld≤2	Poor
2<Ld	Terrible

6. Conclusion

(1) The EMD decomposition method is introduced to deal with the vibration signal of remanufactured engine, and the correlation coefficient is applied to study the correlation between IMF components and original signal, the correlation coefficient of IMF components of remanufactured engine and normal engine is studied.

(2) Correlation dimension is used to analyze the dynamic structure of IMF component, and a vibration intensity index is put forward to evaluate of remanufactured level with the correlation coefficient and correlation dimension.

(3) The relationship between remanufactured level and vibration intensity value is built. The analyse of vibration signal for remanufactured engine is made, the vibration intensity values shows that the manufactured level is good.

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