Applied Mathematical Sciences, Vol. 4, 2010, no. 34, 1671 - 1679

Research on the State Space Reconstruction Applying in Fault Diagnosis of Diesel Engine

YANG Wei

1. School of Mechanical & Electric Engineering,
Tianjin Polytechnic University, Tianjin, 300160, P. R. China;
2. Tianjin Key Laboratory of Advanced Mechatronics Equipment Technology,
Tianjin Polytechnic University, Tianjin 300160, P. R. China

XU Yu-xiu

1. School of Mechanical & Electric Engineering,
Tianjin Polytechnic University, Tianjin, 300160, P. R. China;
2. Tianjin Key Laboratory of Advanced Mechatronics Equipment Technology,
Tianjin Polytechnic University, Tianjin 300160, P. R. China
www.yangwei@qq.com

Abstract

Analyzing the data of diesel surface vibration acceleration monitoring, the method of state space reconstruction was applied. Processing the vibration acceleration signal via integration and filtering, displacement sequence of superficial low frequency vibration was acquired. The appropriate parameters were selected for reconstructing state space of the system based on the analysis of the displacement sequence. The experimental results representing the normal and fault state were obtained by using methods of Phase Diagram Analysis, largest Lyapunov exponent analysis and Principal Component Analysis (PCA). Both the research results and practical examples show that this method is effective in dynamical analysis and fault diagnosis. It can distinguish between normal state and fault state of diesel engine intuitively and clearly.

Keywords: State space reconstruction, Phase Diagram Analysis, largest Lyapunov exponent analysis, Principal Component Analysis, Fault diagnosis

1. Introduction

The surface vibration signal of diesel is non-stationary signal and consists of multiple components. This complexity is due to all kinds of factors such as the impact forces/moments, excitations, as well as the complex and variable transfer path and so on. Owning to this characteristic and some restricts from practical measurement (such as the number and position of measurement points), it is difficult to use the fault diagnosis method of impulse-response module which based on structural dynamics. How to extract more useful information from the signal of limited measuring point effectively becomes an urgent issue in the practical diagnosis. The traditional researchers focus on finding and validating the signal parameter model which is concerned with the machine's normal or abnormal working state. But the traditional method is lacking of the intrinsical cognition of the machine dynamic. In recent years, the development of diagnosis method based on the state space reconstruction has made our apprehensions concerning the character of diesel's vibration signal and the whole system more deeply. However, as far as the discussion of how to select time series of the original signal is seldom mentioned. When it comes to the pretreatment of series, people only discussed a little noise reduction, much less the decomposition and transform of the signal series. In views of the complexity of practical system, it is necessary to take the selecting of valid signal and pretreatment technology into account when doing the analysis of state space reconstruction.

In this paper, the acceleration series of the original surface vibration signals were processed via integration and filter, displacement sequence superficial low frequency vibration was acquired. And then using this displacement series reconstructed state space smoothly and clearly. It can effectively extract the fault character and diagnosis analysis by doing the above process.

2. Character of diesel surface low frequency vibration and the obtaining of vibration displacement signal

The whole diesel acts as a big oscillator and oscillates in its elastic support. Its exciting-vibration forces contain reciprocating inertial force (piston and connecting pole); centrifugal force (crank groupware and connecting pole); swing inertial moment; subversive inertial moment(which is caused by the variety of load or speed); inertial force and moment which come from the vibration of basement or vehicle frame, etc[7]. The low frequency vibration signal coming from diesel surface takes great proportion in the whole vibration energy, and its vibration acceleration signal can directly reflect multiple impacts, therefore it is improper to reconstruct scalar quantity series from the acceleration signal. Reconstructing smooth and clear state space using displacement series can effectively extract characteristic and diagnosis fault.

The displacement series can be obtained by means of low-pass filtering, extracting and integral to the acceleration series. And the signal process of getting vibration displacement series is shown in figure 1. In order to get the character of linear phase, FIR numeric filters are used. It usually uses window's function while designing, and Blackman windows are good to the side-lobe suppression. Finally, the surface low frequency displacement signal which is obtained by above processing makes favorable foundation to the reconstruction and analysis of the state space.

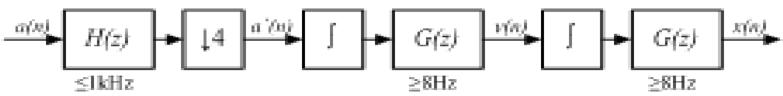


Fig.1 The signal process of getting low frequency vibration displacement sequence form original acceleration sample data

3. State space reconstruction analysis of vibration signal

Many researches indicate that the diesel's surface vibration signal is deterministic chaos [3], therefore it is proper to post the dynamic character of the surface vibration according to the theory and method of non-linear dynamic. By analyzing the whole dynamic character and its variation, the condition of the system's dynamic construction can be deduced, and then the machine's work condition is grasped. In every non-linear dynamic analysis method, the reconstruction and analysis based on reconstruction have decisive effect on the analysis framework. The reconstruction and state space analysis method are briefly mentioned as follows.

3.1. Delay coordinates state space reconstruction

As far as the state variable $S(t)$ which comes from first order system of p dimension, then equation is that: $S(t) = [s_1(t), s_2(t), \cdots, s_p(t)]^T$, while its second order differentiable scalar quantity function is as follows:

$$x(t) = f(S(t))$$
$$(f : \mathrm{R}^p \to \mathrm{R}, S \mapsto f(S), f \in C^2(\mathrm{R}^p)),$$

And consuming its sampling time interval as τ_s and $\{x(t_i) = x(t_0 + (i-1)\tau_s) = x_i\}_{i=0,1,2,3,\cdots}$. If embedded dimension m ($m \geq 2d+1$, and d is attractive sub-dimension) and lag time τ_d ($\tau_d = t_d \tau_s (t_d \in \mathrm{N})$) are properly selected, and delay coordinate series will be established as follows:

$$Y(t_i) = (x(t_i), x(t_i + \tau_d), x(t_i + 2\tau_d) \cdots, x(t_i + (m-1)\tau_d))^{\mathrm{T}}$$
$$= (x_i, x_{i+t_d}, \cdots, x_{i+(m-1)t_d})^{\mathrm{T}}$$
$$(i = 0, 1, 2, 3, \cdots)$$

Based on Takens theory, phase state space reconstructed from $Y(t_i)$ will resume the dynamic characteristic of the original system attractors in the topology equivalence meaning [1, 2, 4].

(1) The determination of reconstruction parameters

Generally speaking, at first the attractors' dimension *d* is estimated by G-P algorithm in order to determine the lower limit of embedding dimension *m*; and then lag time τ_d is properly selected by means of the following methods such as auto-correlation algorithm, average displacement (AD) algorithm, complex auto-correlation algorithm, mutual information algorithm or C-C algorithm and etc. In most of the methods m is finally determined by experiment. Whereas as far as the C-C algorithm is concerned, *m* is properly determined at the mean time of selecting τ_d , therefore the scale has little effect on the characteristic of selective correlation. After numerical computation we found that the largest Lyapunov exponents whose parameters are calculate by the C-C algorithm are much more stable and exact (In this article this statement has been validated by means of Chen's system and Lorenz system), that is the reason why the C-C algorithm is adopted in this paper.

(2) C-C algorithm

The correlation of lag time series which are waiting for selected is determined by correlative integral windage of a group of particular dimensions. It is demanded that the combination of (τ_d, m) must be proper in order to make the absolute value of correlative integral windage smaller and the warp varies little while scale is different, and that lag time window condition $\tau_w = (m-1)\tau_d > \tau_p$ (τ_p is the basic cycle of scalar quantity series) must be satisfied[6].

3.2 Fault analysis based on reconstruction

The attractors' topology structure and geometry characteristic are analyzed from the reconstruction phase or three-dimensional phase orbit. After reviewing the orbit embranchment and the geometry aberrance of the orbit, we find that the variation of the system's dynamic parameters or outside environment may cause the change of balance and establish the new balance [7].

(1) Largest Lyapunov exponent analysis

The largest Lyapunov exponents are used to describe the basic characteristic parameters' stability or non-stability of the system moving orbit. It reflects the system's whole dynamic character and has very important meaning of researching the system's dynamic structure. The value of Lyapunov exponents can basically distinguish the system's every kind of balance points, and its variation reflects the in-and-out factors which lead to balance diversion, just as the variation and effect of system's parameters and influence factors coming from outside. A valid algorithm of solving largest Lyapunov exponents by practical data is small data sets[6]: Consuming that $Y(t_j)$ is the neighbor of $Y(t_i)$, that is to say in all phase points coming from different basic period of $Y(t_j)$, what we concern is the smallest distance between $Y(t_j)$ and $Y(t_i)$, the distance and distance after k steps evolving are separately defined as :

$$d_i(0) = \left\|Y(t_j) - Y(t_i)\right\| = \min_{\substack{0 \le \hat{j} \le M \\ |t_{\hat{j}} - t_i| > \tau_p}} \left\|Y(t_{\hat{j}}) - Y(t_i)\right\| \qquad (1)$$

$$d_i(k) = \left\|Y(t_j + k\tau_s) - Y(t_i + k\tau_s)\right\| \qquad (2)$$

And τ_s is a step time interval in lag coordinates series, because the largest Lyapunov exponents are superior during evolving, therefore following relations are self-evidence,

$$d_i(k) \approx \exp(\lambda_1 k\tau_s) d_i(0) \qquad (3)$$

$$\ln d_i(k) \approx \lambda_1(k\tau_s) + \ln d_i(0),$$
$$0 \le i \le M-1, Ne_{\min} \le k \le Ne_{\max} \qquad (4)$$

λ_1 is slope in the above lines, after fitting the estimation will be obtained. $Ne_{\min}$ is the least evolving times and $Ne_{\max}$ is the most evolving times. According to selecting linearity range of practical relation curvilinear to ascertain the values of $Ne_{\min}$ and $Ne_{\max}$, and to minimize the estimation fluctuating of slope.

(2) Principal component analysis (PCA)

The lag coordinates vectors series are regarded as sampling series of multivariate stochastic vectors, and estimating covariance matrix S of every unit in stochastic vectors. The estimation of S is [5]:

$$S = \frac{1}{M-1}\sum_{i=0}^{M-1}(Y(t_i) - \overline{Y})(Y(t_i) - \overline{Y})^{\mathrm{T}},$$

$$\overline{Y} = \frac{1}{M}\sum_{i=0}^{M-1} Y(t_i) \qquad (5)$$

If $\lambda_1 \ge \lambda_2 \ge \cdots \ge \lambda_m \ge 0$ is the eigenvalue of S, and that eigenvalue is the principal component. $a_1, a_2, \cdots, a_m$ are the corresponding eigenvectors. Therefore the principal component can be defined as follows'

$$Z_k(t_i) = a_k^{\mathrm{T}}(Y(t_i) - \overline{Y});$$
$$(1 \le k \le m, 0 \le i \le M-1) \qquad (6)$$

The k th contribute rate of principal component is defined as $\lambda_k / \sum_{i=1}^{m} \lambda_i$.

The corresponding eigenvalues of principal component are orthogonal each other, and their combination make a particular orthogonal coordinate of the state space reconstruction. In this coordinate, all attractors orbits' projection movement ahead of k are the original orbit movement optimal linear k dimensions approximately in the least meaning of remnant sum of squares. In the condition of abnormal or fault, the moving state is usually more un-regular and complex, therefore the moving energy of high step principal component will accrete and the distribution of moving energy will be variable to different fault. That is to say, the system's dynamic structure can be researched by means of analyzing every principal component's movement and its correlation.

4. State space reconstruction of low frequency vibration in the application of fault diagnosis

(1) Analysis of reconstructing phase space

The signal data comes from diesel of WD615, the test working conditions are fuel stop of every cylinder at different time and making bigger clearance of in-let valve, the sampling frequency is 10240Hz. The vibration displacement is solving and phase space is reconstructed. Observing the phase space reconstruction and making some comparison, we can find that the orbit of normal state just as shown on fig.2, and that orbit becomes wider and polarization caused by flameout as fig.3 showing. Losing most impulse force caused by flameout can lead to balance transferring(away from normal balance state) ,and thus causing orbit branches; The fluctuation caused by in-let valve of No.6 cylinder impacting leads to phase space orbit which reconstructs from low frequency vibration signal is partly geometry aberrance, and just as shown in fig.4.

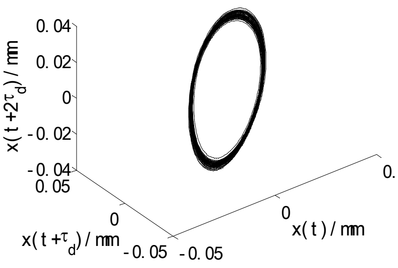


Fig.2 Trajectory in reconstruct state space based on normal condition

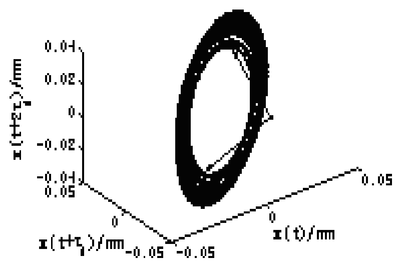


Fig.3 Trajectory when cut the fuel supply of cylinder 2

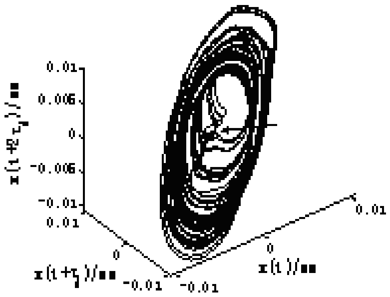


Fig.4 Trajectory in reconstruct state space under inlet valve back to pose impact of cylinder 6

(2) Largest Lyapunov exponent's analysis

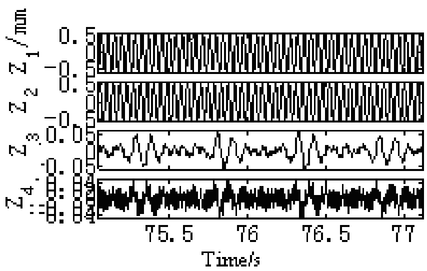
After observing the variation of largest Lyapunov exponent in the course of flameout, we can find that the value arrives its maximum in the transition process, and in normal condition its value is usually more than five while in the condition of fuel stop it is less than five. In a certain speed range, this conclusion is tenable to every cylinder fuel stop. The average exponent value is less than five while the clearance of cylinder 6 is extremely big. It is illuminated that the largest Lyapunov exponents can really reflect the variation of the system's dynamic characteristic in the condition of normal or fault.

(3) Principal components analysis

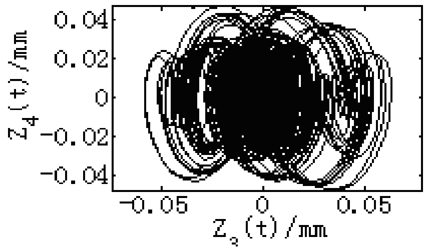
Reconstructing the following signal with eight working cycles and in three different working condition (normal, in-let valve noise of No.6 cylinder and flameout of cylinder 2), then solving the corresponding eigenvalue of principal components, the contribution rate of principal component is obtained just as fig.5 shown. From fig.5 we can find that in normal condition finite high frequency components will be contained in the high step principal component moving fluctuation, and that in fault condition, the high frequency components almost disappear. Therefore waveform becomes more smoothly and with complex and rhythm fluctuation. Because the movement of the system is much more smoothly and this can reflect that in fault condition high step principal components have more contribution rate to system movement. The phase diagrams are different from each other in three different conditions. That is to say, principal components parameters can be used as the characteristic parameters of fault diagnosis.

While the diesel is working in different conditions, and the amplitude of principal components' moving may be different, and then the variation of amplitude is ascertained.

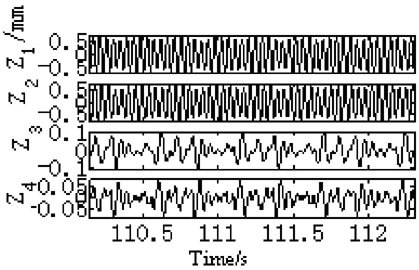
Those rules show that it is meaningful to research the state space reconstruction orbit moving based on principal components.



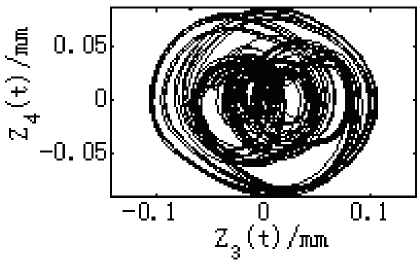
(a) Normal waveform



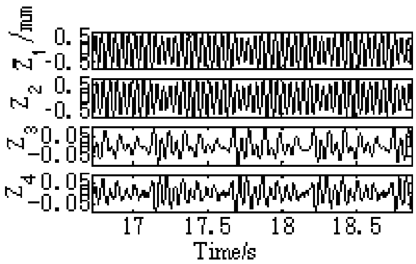
(b) Z3/Z4 phase diagram in normal condition



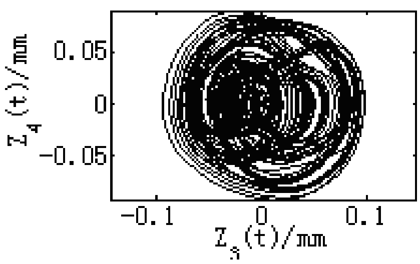
(c) Waveform of 2nd cylinder flameout



(d) Z3/Z4 phase diagram while 2nd cylinder flameout



(e) Waveform while valve clearance



(f) Z3/Z4 phase diagram while valve clearance becomes bigger of 6th cylinder

Fig.5 Former 4 steps prime component of lag coordinate series in different working condition

5. Conclusions

(1) The pre-treat filtering method of scalar quantity sampling series which is used for state space reconstruction is also valid to reduce noisy and complex dynamic behavior of non-correlative system.

(2) The obtained flameout and in-let valve noise fault signal are analyzed by the following method: Phase diagram analysis; Lyapunov exponent analysis and PCA analysis using the state space reconstruction of low frequency vibration displacement. The result shows that this method can clearly and directly distinguish the normal or fault state of the diesel.

(3) The calculation of largest Lyapunov exponents shows that surface low frequency vibration displacement signal is also deterministic chaos.

(4) The principal components moving analysis is a practical reducing dimensions method in researching state space movement. It's essential a certain optimal orthogonal decomposition of the system's orbit moving in state space reconstruction.

References

[1] CHEN Yushu, Nonlinear dynamical principle of mechanical fault diagnosis, Chinese Journal of Mechanical Engineering, 43(1), (2007), 25-43.

[2] DING Wangcai, XIE Jianhua. Advances of research on bifurcations and chaos in vibro-impact system. Advances in Mechanics, 35(4), (2005), 514-515.

[3] JIN Ping, CHEN Yiran, BAI Ye, Study on features of surface vibration signals of the internal combustion engine, Journal of Tianjin University, 33(1), (2000), 65-66.

[4] KANTZ, H. &SCHREIBER, T. Nonlinear Time Series Analysis, Beijing: TSINGHUA University Press, 2001, 135-138.

[5] GAO Huixuan, Application Multivariate Statistical Analysis. Peking University Press, 2005, 263-290.

[6] LV Jinhu, LV Junan, CHEN Shihua, Analysis and application of chaotic time series, Wuhan University Press, 2000.

[7] SCHEINERMAN. E. R., Invitation to dynamical systems, New York: Pearson Education, 1996, 119-121.

Received: November, 2009