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WHEELSET BEARING VIBRATION ANALYSIS BASED ON NONLINEAR DYNAMICAL METHOD

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ABSTRACT

The wheelset bearing play an important role in train running safety. In this paper, we introduce the nonlinear dynamical method to study the wheelset bearing vibration signal. Based on the comparative studies of the phase graph and the correlation dimension of the vibration signals under normal condition, outer peeling fault condition and rolling element electric erosion fault condition, the following conclusions are shown: (1) The dynamical behavior of the wheelset bearing with fault is complicated than of the normal condition. (2) The correlation dimension of wheelset bearing is different under normal, outer peeling fault and rolling element electric erosion fault conditions. The correlation dimension can be used in wheelset bearing health monitoring. Therefore, it is quite reasonable to fault diagnosis of wheelset bearing to use nonlinear dynamical method.

Keywords: *Nonlinear Dynamic, Phase Space, Correlation Dimension*

1. INTRODUCTION

The fault of wheelset bearing is one of the most important factors to the safety of the train running. Since the vibration signal of the bearing is usually nonlinear and non-stationary. So the signal processing methods such as Wavelet Transform[1, 2] and Empirical Mode Decomposition[3] have been used widely in vibration signal analysis. The nonlinear dynamics theory has brought new methodologies to analysis nonlinear vibration behavior of mechanical system.

Nowadays, the application of nonlinear dynamics in fault diagnosis is a very active research field. It is well known that as a machine fails, the vibration characteristics of the machine are changing and nonlinear dynamical analysis techniques may be the most suitable methods for various aspects of machinery analysis including fault detection and diagnosis [4]. Alberto et al. [5] shown that correlation dimension can use for on-line condition monitoring of large rotating machinery. In [6], the correlation dimension is applied for gearbox fault diagnosis. In [7], some non-linear diagnostic methods for rotating machinery are used such as pseudo-phase portrait, singular spectrum analysis and correlation dimension. In [8], the pseudo-phase portrait is used to extract qualitative features of machine faults. The results show that pseudo-phase portrait is sensitive to some fault types.

In this paper, we apply nonlinear dynamical method to wheelset bearing vibration signal analysis. Experiments are conducted on the wheelset bearing test rig under different conditions, and the vibration signal with normal, outer peeling fault and rolling element electric erosion fault are analyzed. The structure of this paper is as follows: In Section 2, the theoretical background of the phase space reconstruction and correlation dimension is given. In Section 3, the application of the phase space reconstruction and correlation dimension to the wheelset bearing vibration signal analysis. Finally, the main conclusions are given in Section 4.

2. THEORY

2.1 Reconstruction Of The Phase Space

The embedding procedure is the first step of the phase space reconstruction of a dynamical system from the observation of a single variable. The phase space reconstruction is the method of delays [9].

For an N-point time series {x1, x2, ⋯, x_n}, a sequence of vectors y_i in a new space can be generated as

$$y_i=\{x_i, x_{i+\tau}, \cdots, x_{i+(m-1)\tau}\},\quad i=1,2,\cdots, n-(m-1)\tau$$

Where m is the embedding dimension of the reconstructed state space, τ is called the lag time

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measured in units of sampling interval. The *m* co-ordinates of each point y_i are samples from the raw time series covering an embedding window of length $(m-1)\tau$. The space which is reconstructed from a raw time series will be called the embedding space and its dimension the embedding dimension.

The phase space reconstruction consists of determinations of the lag time τ and the embedding dimension *m*. There have several methods to determine these parameters. The lag time τ can be determined by autocorrelation function, mutual information [10], etc. In this paper, the mutual information method was used. The mutual information is given by [11]:

$$I = -\sum_{ij} p_{ij}(\tau)\ln\frac{p_{ij}(\tau)}{p_i p_j} \quad (1)$$

Where for some partition on the real number p_i is the probability to find a time series value in the *i*-th interval, and $p_{ij}(\tau)$ is the joint probability that an observation falls into the *i*-th interval and the observation time τ later falls into the *j*-th. There exist good arguments that if the time delayed mutual information exhibits a marked minimum at a certain value of τ, then this is a good candidate for a reasonable time delay.

The definition of the embedding dimension was taken according to the Takens' theorem, where the number of *m*-reconstructed vectors should be $m \geqslant (2D_2+1)$.

2.2 Correlation Dimension

Correlation dimension is a measure of the extent to which the presence of a data point affects the position of other points lying on the attractor. The reconstruction of the phase-space of a time series and, hence, its attractor is an important first step in the correlation dimension method. Such a reconstruction approach uses the concept of embedding a single-variable series in a multi-dimensional phase space to represent the underlying dynamics.

The correlation dimension is derived from the correlation function, which is a cumulative correlation function that measures the function of points in the m-dimensional reconstructed space. For an m-dimensional phase space the correlation function *C*(*r*) is given by [12]:

$$C(r) = \lim_{N\to\infty}\frac{2}{N(N-1)}\sum_{1\le i<j\le N}^{N} H(r-|Y_i - Y_j|) \quad (2)$$

Where *H* is the Heaviside step function, with $H(u)=1$ for $u>0$, and $H(u)=0$ for $u\le 0$, where $u=r-|Y_i-Y_j|$, N is the number of data points, *r* is the radius of the sphere centered on Y_i or Y_j. If the time series is characterized by an attractor, then for positive values of *r* the correlation function *C*(*r*) is related to the radius *r* by the following relation:

$$C(r) \propto \alpha r^{D_2} \quad (3)$$

Where α is a constant. The correlation dimension D_2 is defined as follows:

$$D_2 = \lim_{r\to 0}\frac{\log C(r)}{\log r} \quad (4)$$

The slope is generally estimated by a least squares fit of a straight line over a certain range of *r*, called the scaling region.

3. EXPERIMENT AND RESULT

The wheelset bearing vibration signals obtained from the institute of Traffic Environment and Safety Engineering, Shijiazhuang Tiedao University. The wheelset test rig was shown in Figure 1. Data was gathered for three different conditions: (1) normal condition; (2) outer peeling fault condition; (3) rolling element electric erosion fault condition. The bearing type is 197726.The outer peeling fault bearing was shown in Figure 2. The Bearing with rolling element Electric erosion fault was shown in Figure 3. Wheelset bearing Vibration data were collected using accelerometers attached to the test rig support. The sampling frequency is 5 120 Hz.

Figure 1: The Wheelset Test Rig

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Figure 2: Wheelset Bearing With Outer Peeling Fault

Figure 3: Wheelset Bearing With Rolling Element Electric Erosion Fault

3.1 Determine the Time Delay

The time delay τ and embedding dimension *m* were determined for reconstruction of the wheelset bearing dynamics. The mutual information function of the normal bearing, outer peeling fault bearing and rolling element electric erosion fault were calculated to determine the time delay. Figure 4 shows the mutual information of the normal wheelset bearing. After several experiments with the three wheelset bearing condition the optimal time delay τ was chosen as 3 since the mutual information reached to the first minimum value.

The optimal embedding dimension was found according to Cao's method. There's a kink in Figure 5 produced by Cao's method at 4. So embedding dimension was chosen as 4. The time delay and minimum embedding dimension were found for all the normal, outer peeling fault and rolling element electric erosion fault signal.

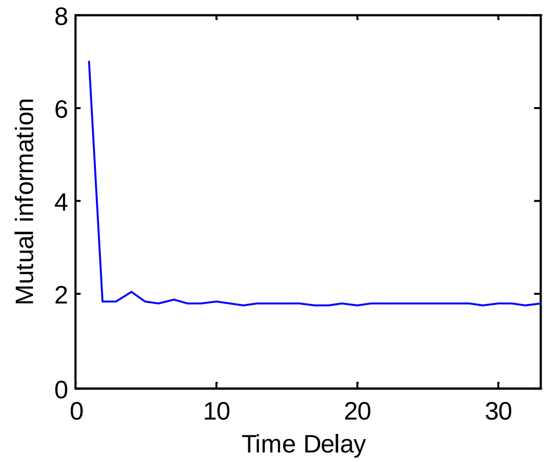

Figure 4: Determination Of The Time Delay

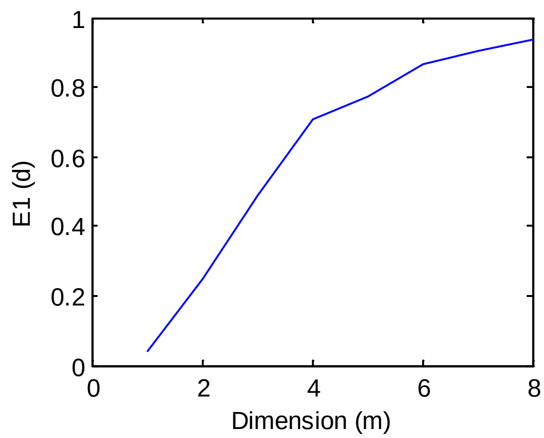

Figure 5: Determination Of The Embedding Dimension

3.2 Two-Dimensional Phase Plots

Figure 6 shows the two-dimensional phase plots to depict the graphical dynamics of the normal bearing. Figure 7 shows the two-dimensional phase plots to depict the graphical dynamics of the outer peeling fault bearing. And Figure 8 shows the two-dimensional phase plots to depict the graphical dynamics of the rolling element electric erosion fault bearing. The delay parameter τ used in the figures is 3, the data length is 6 000 to sufficiently depict the dynamics. The figures show that the three plots are different from each other which indicate the different of their dynamics within the manifold. The outer peeling fault and the rolling element electric erosion fault bearing dynamics appear more complicated than the normal bearing.

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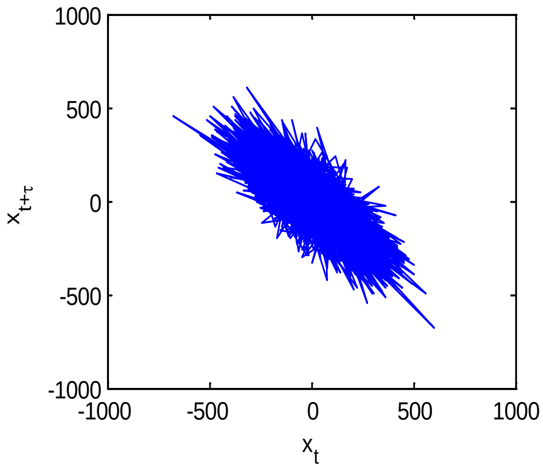

Figure 6: Two-Dimensional Phase Plots Of Vibration Signal Of Normal Wheelset Bearing

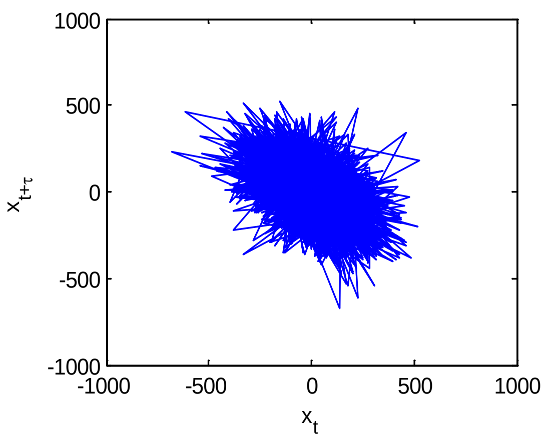

Figure 7: Two-Dimensional Phase Plots Of Vibration Signal Of Outer Peeling Fault Wheelset Bearing

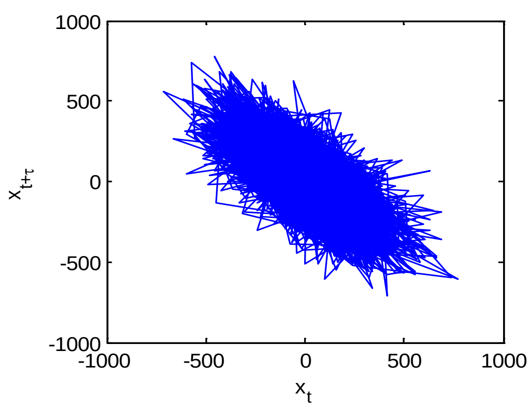

Figure 8: Two-Dimensional Phase Plots Of Vibration Signal Of Rolling Element Electric Erosion Fault

3.3 Correlation Dimension

The correlation functions and the exponents are computed for the time series of normal, outer peeling fault and rolling element electric erosion fault wheelset bearing. The correlation dimension is related with the embedding dimension. The correlation dimension of wheelset bearing with different embedding dimension was shown in Figure 9. It can be seen that increasing the embedding dimension *m* makes it possible to recognize the outer peeling fault and the rolling element electric erosion fault. With the growth of the embedding dimension the correlation dimension of normal and outer peeling fault wheelset bearing demonstrate divergence. And it can be seen in Figure 9 that the correlation dimension in outer peeling fault and rolling element electric erosion fault are higher than the normal state with higher embedding dimension.

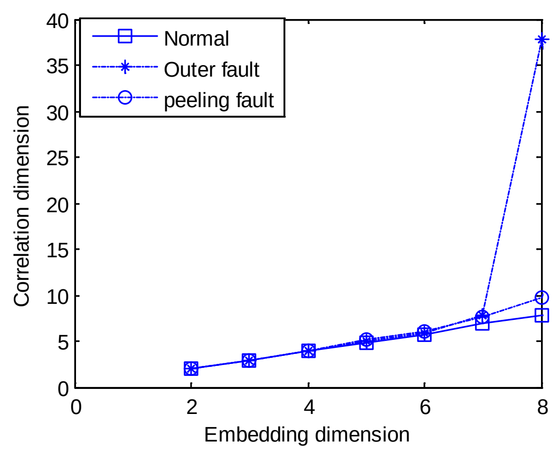

Figure 9: The Dependence Of The Correlation Dimensions Of The Wheelset Bearing With Different Embedding Dimension

4. CONCLUSION

The wheelset bearing vibration experiments have been done on test rig. The analyses on phase graph and correlation dimension of normal, outer peeling fault and rolling element electric erosion fault of wheelset bearing vibration signal have been done. Observing Figure 6-8, the wheelset bearing vibration signal evolve from more complicated and disordered phase state when fault occurred. From Figure 9 we can see that the Correlation Dimension of wheelset bearing signals become larger in fault condition. These results indicate that the Correlation Dimension of wheelset bearing vibration signal can reflect the fault state of wheelset bearing.

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