Chaotic Characteristics Study on Cylinder Liner-Piston Ring’s Friction Signal

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Abstract. Cylinder linear-piston ring is the most important friction pairs in the internal combustion engine and the friction signal can reflect the characteristics of the whole tribological system. The wear test was carried out using UMT-3 tester and the friction signal was denoised via wavelet technology for the determination of chaotic characteristics by principal component, the largest Lyapunov exponent and the Kolmogorov entropy. The results indicated that chaos theory is applicable to the research of cylinder linear-piston ring wear system due to its chaotic characteristics, which is of great significance to the tribological design and the identification of the state of wear process.

1. Introduction

Chaos is a common phenomenon in complex nonlinear systems. Although chaos has been found in various dynamic systems in the past few decades, the research on chaotic characteristics in tribology starts late. Andrzei [1] used phase space reconstruction techniques to study the chaotic behaviour of irreversible dry friction and pointed out that the tribological system had certain dynamic characteristics, but it is not a simple mapping from one coordinate system to another. Based on the calculation of power spectrum, correlation dimension and largest Lyapunov exponent of actual friction signal, Zhu and Ge [2] verified the chaotic characteristics of the friction system and furthermore, they defined the running-in process as the self-organizing process between the two friction surfaces [3,4]. After the research on fractal and chaos characterization of worn surface topography and friction signal during the running-in process, the concept of running-in attractor was put forward for the first time. Zhu [5] redefined the three stages of the wear process on the basis of chaotic theory and studied the evolution rule of the running-in attractor during the whole wear process based on the phase space reconstruction of the friction signal time series.

As the most important reciprocating friction pairs in the internal combustion engine, the piston ring plays an essential role for the sealing of cylinder linear to prevent gas leakage and excessive lubricant entering the combustion chamber. Therefore, the friction signal of the wear process contains abundant information that can reflect the characteristics of the whole tribological system. Whether the friction signal has the chaotic characteristics, and whether the chaotic characteristic parameters change during the wear process and how they change. The in-depth study of these problems will make contribution to fully understand and grasp the dynamic behaviour rules of wear process.
2. Friction test
In this paper, the UMT-3 universal friction and wear tester was used to simulate the friction and wear process of cylinder liner piston ring in actual internal combustion engine. The samples used in the test are all from the piston ring and cylinder liner of the actual internal combustion engine system. Prior to the test, the piston ring and cylinder liner were cut into blocks respectively, the upper specimen is a piston ring specimen and the lower sample is a cylinder liner. The chromium piston ring manufactured by Yizheng double-ring piston ring company was chosen for the test, which is applicable to the bore of cylinder linear 110 mm. However, the radius of the piston ring is greater than 110 mm at free state, the cylinder liner used in the test was suitable for Steyr WD 615.68 diesel engine with diameter of 126 mm. As shown in Figure 1, the specimen size of piston ring and cylinder linear are $12.8 \times 2 \times 5$ mm and $43.2 \times 30 \times 2$ mm respectively, which were obtained via wire cutting method. The nominal contact area of the piston ring and the cylinder liner is 25.66 mm$^2$. In this paper, a group of tests were designed to obtain the actual friction signal, and the parameters of the test conditions are shown in table 1. Before each test, 0.2 ml CD grade 15W-40 diesel engine oil was used for lubrication via a medical syringe.

Table 1. Experimental condition parameters

| Frequency $f$/Hz | Speed $v$/m/s | Load $P$/N | Temperature $T$/°C | Distance $s$/mm |
|------------------|---------------|------------|--------------------|-----------------|
| 5                | 0.2           | 20         | 20                 | 20              |
|                  |               | 30         |                    |                 |
|                  |               | 40         |                    |                 |
|                  |               | 50         |                    |                 |
| 15               | 0.3           | 200        | 200                | 10              |

(a) piston ring                    (b) cylinder linear
Fig 1. Piston ring and cylinder linear segments

3. Extracting and denoising of friction signal

3.1. A subsection Friction signal extraction
All the data were captured via in-built acquisition module in UMT-3 with real-time continuous measurement and storage, the sampling frequency was 1 KHz. After each test, the stored data was extracted using Viewer software and saved as a data file format that is easy to handle. This paper mainly uses Origin (version 9.1, Originlab, USA) and Matlab (version 8.3, Mathworks, USA) software for further analysis and data processing.

Figure 2 demonstrates the time sequence diagram of the friction signal during the whole wear test process under the condition of loading 200 N, speed 0.3 m/s and temperature 200° C, which was drawn using Origin software based on the data derived from Viewer software.
3.2. Friction signal denoising
Due to the unavoidable noise in the test process, which could influence the computation of chaotic characteristic parameters. Therefore, the wavelet technology was applied to denoise the original friction signal. The comparison of a friction signal before and after denoising was illustrated in Figure 3. It is obvious that the high frequency noise signal was filtered out after wavelet denoising. Thus, all the measured time-series signal need to be denoised prior to the analysis for accurate computation.

4. Inspection of friction signal’s chaotic properties
Before analyzing the chaotic signal from the actual system, the chaotic characteristics of the time series signal should be investigated to determine whether the system is chaotic. There are various methods to verify the chaotic/nonlinear characteristics of time series signal. In this paper, the power spectrum, principal component, largest Lyapunov exponent and Kolmogorov entropy were analyzed for the determination of chaotic characteristics of friction signal.

4.1. Power spectrum
The power spectrum method was used to observe the nonlinear characteristics of the friction signal intuitively, which is detailed as follows: 1) the estimation of the autocorrelation function of the time series; 2) the spectral estimation of the time series is obtained by the fast Fourier transform of the autocorrelation function. By observing the power spectrum, if the spectrum has a single peak or a few peaks, it corresponds to a periodic or quasi-periodic sequence; if there is no obvious peak or even a piece, it corresponds to the aperiodic sequence.

With the help of MATLAB software, the power spectrum of time series signal can be easily and quickly realized. Figure 4 (a) demonstrates a power spectrum of a sinusoidal signal (sin(2πx/10), x=1:1:2500) and it is obvious that there is one peak in the power spectrum for periodic signal. While analyzing the power spectrum of the Lorenz signal, Figure 4 (b) illustrates no obvious peak for chaotic signal. Therefore, the power spectrum method can be used to determine whether the signal studied is nonlinear/chaotic.
It is easy to see from Figure 5 that the power spectrum of a segment of friction signal has a wide continuous power spectrum and per this, the nonlinear characteristics of the friction force signal can be determined preliminarily.

4.2. Principal component
The principal component analysis (PCA) can be used to distinguish noise signal and chaotic signal due to the significant difference of principal component distribution. The principal component spectrum of the chaotic signal is an approximate straight line with the negative number of the slope, and the principal component spectrum of the noise signal is a straight line that is parallel to the transverse axis. The principal component spectra of the white noise signal, Lorenz signal, and friction signal are illustrated in Figure 6, respectively. Obviously, the principal component spectrum of noise signal is a nearly straight line parallel to x axis, while the spectrum of friction signal is an approximate straight line with negative slope, which is very similar to the spectrum of Lorenz signal. These further identified that the friction signal has chaotic characteristics.

4.3. Largest Lyapunov exponent
The largest Lyapunov exponent is an important parameter for diagnosing and describing the chaos of dynamic system. It is also an important basis for the existence of chaos, that is, as long as it is greater than zero, the existence of chaos can be affirmed.

The relationship between the largest Lyapunov exponent of the two frictional signal time series under the load of 50 N and 60 N and embedding dimension was calculated respectively, which is shown in Figure 7. The maximum Lyapunov exponent decreases with the increase of embedding dimension and tend to be saturated and always greater than zero when the embedding dimension increases to a certain level, which further validate the chaotic characteristics of the friction signal.
Fig 6. Principal components’ spectrum plots

(a) white noise signal  
(b) Lorenz signal  
(c) friction force signal

Fig 7. The maximum Lyapunov exponent of frictional signal

4.4. Kolmogorov entropy

The Kolmogorov entropy of the friction signal time series was calculated to further distinguish the chaotic characteristics of friction signal with frequency of 100 Hz and data length of 5000 points. The change law of the Kolmogorov entropy with the change of the embedding dimension is demonstrated in Figure 8.
Fig 8. The results of Kolmogorov entropy calculation

With the increase of the embedding dimension \( m \), the value of Kolmogorov entropy gradually tends to be stable and converges to a fixed value, and is always greater than zero. According to the criterion \( 0 < K < \infty \) means the chaotic motion of the system and it can be determined that the friction signal is chaotic.

5. Conclusion

In this paper, the wear tests of cylinder linear - piston ring were carried out using the UMT-3 universal friction and wear tester. The actual working condition of cylinder linear - piston ring is simulated from the aspects of sample selection, movement mode and operating condition. The friction signal obtained was processed by wavelet technology for denoising and then determined its chaotic characteristics by principal component, the largest Lyapunov exponent and the Kolmogorov entropy. The results indicated that the friction signal of cylinder linear - piston ring wear system has typical chaotic characteristics with continuous bandwidth power spectrum, an approximate straight line with a negative slope of principal component spectrum, a positive maximum Lyapunov exponent and Kolmogorov entropy. Thus, the chaotic theory can be used to study the dynamic behavior of the cylinder linear - piston ring wear system, which will be of great significance to the tribological design of cylinder linear - piston ring system and the identification of the state of wear process.

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