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Development of prediction models of running-in attractor

Yuankai Zhou [a,b,c], Xue Zuo [a,b], Hua Zhu [c,*], Tang Wei [c]

[a] School of Mechanical Engineering, Jiangsu University of Science and Technology, Zhenjiang, 212003, China
[b] Jiangsu Provincial Key Laboratory of Advanced Manufacture and Process for Marine Mechanical Equipment, Jiangsu University of Science and Technology, Zhenjiang, 212003, China
[c] School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, 221116, China

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ABSTRACT

Running-in attractor is a stable and time-space ordered structure formed in running-in process. To establish prediction models of the running-in attractor, orthogonal experiments were performed by sliding pins against a disc during the running-in process. The attractors were reconstructed from the measured friction force signals. Their characteristic parameters were computed, and forming time was identified from phase trajectory plot. The variance analysis of characteristic parameters of running-in attractors was conducted to identify the primary and secondary factors for characteristic parameters. The models were established based on response surface method. The running-in attractor can be predicted by the models as long as the working conditions and the initial surfaces roughness are given, which provides reference to running-in design.

1. Introduction

There is temporary fluctuations of friction, temperature and wear rate in the initial sliding between fresh solid surfaces, which is accompanied by the elastic and plastic deformation, workhardening, debris accumulation, interfacial transformation and changes in crystallographic orientation [1]. This process is termed as running in. Since the running-in process is significant for extending the working life of tribosystems and ensuring stable operation, researchers attempt to interpret the complex behavior and realize the active design of running in.

Recent advances have revealed that the tribosystem is a nonlinear dynamic system, featuring with the self-similar structure in wear surface and chaotic regions in friction signals [2–5]. Based on the nonlinear theories, the running-in process was considered as self-organization of contact surfaces [6]. Zhu et al. [7] conducted running-in test by sliding a pin against a disc under lubricated condition, the results demonstrate that harder and smoother surface becomes rougher and its fractal dimension decreases, while the softer and rougher surface becomes smoother and its fractal dimension increases, that is, the counter surfaces adapt and attract to each other. In their further study, the fractal dimensions of friction force and vibration were found to increase gradually during the running-in process and ultimately reach a stable value, which suggests that the friction system is chaotic [8]. The chaos theory has been introduced to study the running-in behavior in recent years. In chaos theory, the attractor is used to describe a chaotic system, such as the Lorenz attractor [9] and the Chen's attractor [10]. It was found that the chaotic attractor in friction system is formed during running-in process by analyzing the phase trajectory of friction signals, therefore, the attractor was termed as running-in attractor [11].

The existence of running-in attractor was verified by the followed-up studies. Zhou et al. [12,13] analyzed friction temperature and friction force signals measured in the running-in process, the results show that the trajectory reconstructed from the signals contract to form chaotic attractor. What is more, the formation of attractor is synchronous for different friction signals originated from the same tribosystem [14]. Sun et al. [15] proposed that the chaotic attractor of the friction vibration gradually converges and tends toward a balanced state in the running-in process.

The concept of running-in attractor or chaotic attractor has been applied on wear fault diagnosis and vibration control over the past few years. For example, Jiang et al. [16] developed a nonlinear dynamic models of gear box taking multi-frequency excitation forces into consideration, based on the models it was found that the chaotic attractor is maintained in steady state, the chaotic degree relates to fault severity, which provided a method of fault diagnosis for gear box. Oberst et al. [17] analyzed the squeal noise in brake system in the perspective of chaotic attractor and proposed a method to suppress noise.

Predicting the running-in attractor is significant to nonlinear

* Corresponding author. University Road, Quanshan District, China University of Mining and Technology, Xuzhou, 221116, China.
E-mail address: zhuhua83591917@163.com (H. Zhu).

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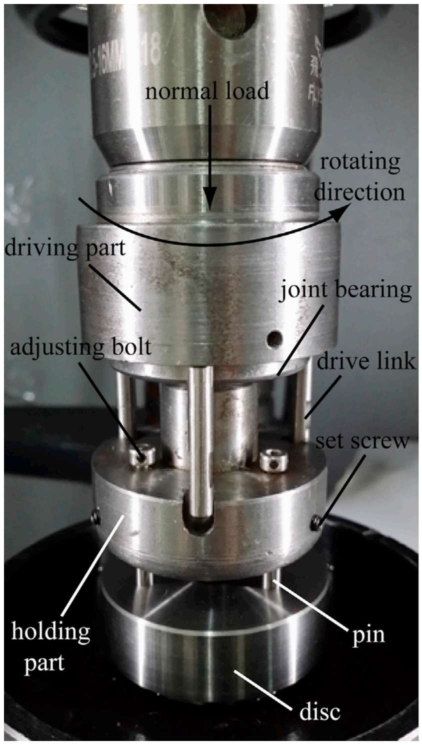

Fig. 1. Pin holder with self-adaptive function. The holding part is connected to the driving part via a joint bearing, so that the pins self-align to the disc.

Table 1
Experimental factors and their corresponding levels.

Factors	Level 1	Level 2	Level 3	Level 4
Initial surface roughness of pin Ra_1 (μm)	0.87	0.58	0.32	0.05
Initial surface roughness of disc Ra_2 (μm)	0.95	0.66	0.35	0.07
Load *P* (MPa)	2.05	3.40	4.75	6.10
Velocity *V* (mm/s)	152	304	456	608

Table 2
Design of experiments.

Test number	Initial surface roughness of pin Ra_1 (μm)	Initial surface roughness of disc Ra_2 (μm)	Load *P* (MPa)	Velocity *v* (mm/s)
1	0.87	0.95	2.05	152
2	0.87	0.66	3.40	304
3	0.87	0.35	4.75	456
4	0.87	0.07	6.10	608
5	0.58	0.95	3.40	456
6	0.58	0.66	2.05	608
7	0.58	0.35	6.10	152
8	0.58	0.07	4.75	304
9	0.32	0.95	4.75	608
10	0.32	0.66	6.10	456
11	0.32	0.35	2.05	304
12	0.32	0.07	3.40	152
13	0.05	0.95	6.10	304
14	0.05	0.66	4.75	152
15	0.05	0.35	3.40	608
16	0.05	0.07	2.05	456

investigation of friction system and real world application. However, the behavior of tribosystem is closely related to working conditions and the initial state, which makes it difficult to model. For example, friction coefficient is sensitive to load, velocity, hardness, melting point and initial surface roughness [18–20]. This paper aims to establish the prediction models of running-in attractor, through which the characteristic parameters and forming time of the running-in attractor can be predicted as long as the load, sliding velocity and initial surface roughness are given. The present paper is organized as follows: In Section 2, running-in tests are performed on a pin-on-disc tribometer under different working conditions, running-in attractors are reconstructed from the measured friction force signals and their characteristic parameters are computed. In Section3, variance analysis of characteristic parameters of running-in attractors is conducted to identify the primary and secondary factors for characteristic parameters. In Section 4, the prediction models of characteristic parameters and forming time of running-in attractor are developed based on the response surface methodology. Finally, the major conclusions are drawn in the last section.

2. Running-in test

2.1. Tribometer

Running-in tests were performed on a pin-on-disc tribometer. Three identical pins were evenly spaced and mounted on a pin holder, which was driven by a motor. The pin holder with self-adaptive function was designed to ensure a good contact between pin and disc. It was composed of driving part, holding part, joint bearing, drive link, adjusting bolt and set screw, as shown in Fig. 1. The length of exposing part of pin could be adjusted by turning the adjusting bolt, which made the end surfaces of the three pins are on a same plane. The pins were locked by set screws. A joint bearing installed in the driving part made pins self-align to the disc. Drive links were used to transmit torque from driving part to holding part. Three degrees of freedom were introduced by a spherical pair in the joint bearing. Since the drive link prevents the holding part from rotating along the axis of driving part, an individual holder has two degrees of freedom. The restricted degree of freedom was compensated by the rotating of spindle of tribometer.

The disc was held static on a disc holder, which was attached to a torque sensor. The torque sensor was used to measure the friction torque signals in the running-in friction process. Friction force was obtained by dividing the friction torque by the average radius of the contact area. The friction force signal was applied to construct the running-in attractor. A normal load was imposed on the contact surface via pin holder.

The material of pin was AISI 52100 with as-quenched hardness of 60 HRC. The pin was 4 mm in diameter and 20 mm in length. The material of disc was AISI 1045 with a hardness of 194 HB and a diameter of 46 mm. The rotating radius of pin was 14.5 mm. The nominal contact area between pin and disc was 37.68 mm^2.

2.2. Orthogonal experiments

Orthogonal experiments were performed to study the influence of working conditions and initial surface roughness on the parameters of running-in attractor. Load, velocity, initial surface roughness of pin and disc were considered as experimental factors. The surface roughness of pin and disc was measured by a JB5C-type stylus profilometer (Taiming Optical Instrument Co., Ltd. Shanghai, China), which has a sampling length ranging from 0.25 mm to 4 mm and a vertical resolution of 0.001 μm. The measurement direction was perpendicular to the texture on the surface. Each surface was measured three times and the average was used for analysis. There were four levels for each factor. The experimental factors and their levels are given in Table 1.

The load was adjusted by weights and the velocity was controlled by frequency converter. The initial surface roughness of pin and disc were obtained by grinding with sandpapers of different grit sizes. A Taguchi $L_{16}(4^5)$ orthogonal array was adopted to design the experiments. The tests arrangement is shown in Table 2. Tests were performed under oil-lubricated conditions. Prior to tests, 0.2 ml lubricating oil, API CD 15W-40, was added to the contact interface of the tribopair. The oil was not supplied any more during the friction test. The friction tests were not terminated until the steady state was attained and sustained for at least