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The nonlinear nature of friction coefficient in lubricated sliding friction

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ABSTRACT

The nonlinear nature of friction coefficient in the lubricated sliding friction is studied. The exponential decay is found in the power spectrum of friction coefficient, which is the characteristic of chaos. Further, the two-order Renyi entropy K_2 is calculated and phase trajectory is plotted. K_2 increases gradually in the running-in friction, stabilizes at a high value in the steady state, and decreases in the increasing friction. The phase trajectory contracts to a smaller size, then moves in a finite space, finally expands rapidly. What's more, the contraction, stabilization and expansion of phase trajectory correspond to the increase, stabilization and decrease of K_2, respectively. Therefore, the friction coefficient in the sliding friction can be described by the chaos theory.

1. Introduction

The friction coefficient, defined as the proportionality of the force opposing relative motion to the force holding the bodies together according to Coulomb's friction law, is a significant parameter in scientific research and engineering application. It is widely used in mathematical modeling of friction and wear, such as friction induced temperature rise model [1], friction induced vibration model [2] and wear prediction model [3]. For the engineering application, on the one hand, the engineers try to obtain a low friction coefficient for the sake of energy conservation in the friction systems such as bearings, guide rail-sliders, piston ring-cylinder liners. On the other hand, they attempt to get relative high friction coefficients in some friction systems like tire-road contacts to ensure driving safety.

In early studies, the friction coefficient of certain friction pair was simply considered as a constant [4]. Researchers attempted to get friction coefficients of various friction pairs through a lot of laboratory tests. However, they are confronted with the problem that the test results are often found different for the same friction pair in different tests. For example, the kinetic friction coefficient of wood on wood is 0.19 in [5], but this value turns to 0.38 in [6], both references lack experimental details because the complexity of friction systems was not well recognized. The friction coefficient depends on the system parameters and friction time which are difficult to keep consistent in each test. As a result, for the same friction pair, the friction coefficients are often different from one test to another.

In recent years, it is generally accepted that the friction coefficient is time-dependent [7]. Poulios et al. [8] found that the friction coefficient is changing with time when measuring the friction coefficient of thermoplastics and fiber composites under low sliding velocity and high pressure. They gave the concept of transient friction coefficient which is measured at a certain point in time, and indicated that further research should pay attention to the evolution of friction coefficient in the friction process. Blau [9] put forward eight commonly observed forms for friction coefficient versus time behavior. In each form, the running-in friction, steady-state and increasing friction can be identified according to the changing tendency of the numerical value of the friction coefficient. In the steady-state, the friction coefficient is relatively stable and the friction system maintains its normal function. Therefore, the friction coefficient measured in the steady-state is used to evaluate the lubricating effect of oil [10], friction-reducing property of surface texture [11] and self-lubricating materials [12].

The friction coefficient is not only time-dependent, but also system-dependent [7,13]. It varies with system parameters including material parameters (hardness, elongation and melting point), surface parameters (surface roughness, surface texture and coating), lubricating parameters (viscosity, density and additives) and parameters relating to working conditions (relative sliding speed, contact pressure, humidity and temperature) [14–17]. Some system parameters such as surface roughness and lubricating properties also vary with time [18,19], which reflects the time-dependence from another perspective. So many factors have an influence on the friction coefficient in a variety of different manners, which leads to dynamic changes of the values of the friction coefficient. Therefore, it is meaningful to investigate the dynamic changes in the friction process, rather than a transient or average value of the friction coefficient [13].

Although researchers have gained profound understanding of friction coefficient, to our knowledge, most previous works have mainly focused on the numerical value of the friction coefficient.

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Recent studies have shown that the tribological system has the nonlinear characteristics, such as fractional dimension and positive Lyapunov exponent [20,21]. The friction coefficient, originating from the tribological system, contains the information which can reveal the nonlinear behavior of the tribological system. Therefore, it is meaningful to study the nonlinear nature of friction coefficients and further reveal the dynamic evolution in the friction process by analyzing the friction coefficient based on chaos theory. This paper is organized as follows. In Section 2, the friction tests are described in detail and the friction coefficient time series is acquired throughout the sliding friction process. In Section 3, the power spectrum of the friction coefficient is obtained based on the periodogram method to detect the chaos. In Section 4, the two-order Renyi entropy is calculated for the quantitative study of the friction coefficient. In Section 5, the phase trajectory is obtained by principal component analysis to reveal the friction attractor. The main conclusions derived from this study are presented in Section 6.

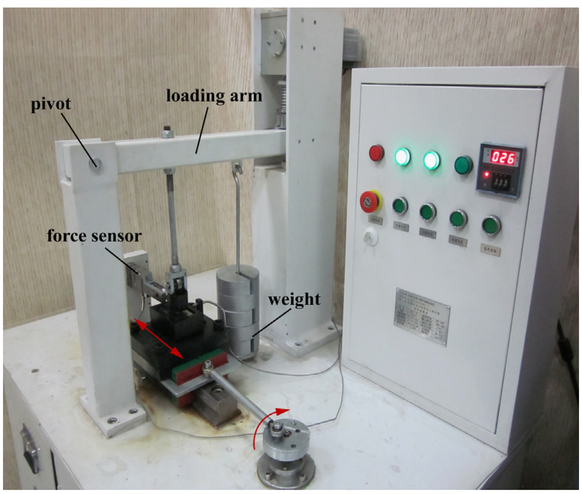

Fig. 1. Photograph of the tribometer.

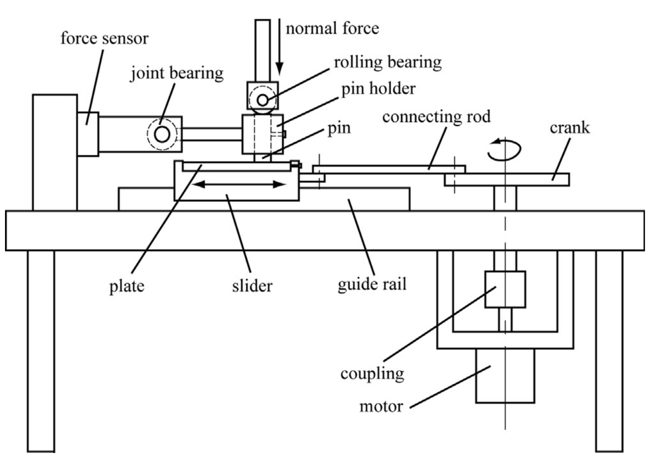

Fig. 2. Schematic of the experimental apparatus.

2. Experiments

2.1. Tribometer

A reciprocating motion tribometer is utilized to perform the experiments. The photograph of the apparatus is shown in Fig. 1, and the schematic is given in Fig. 2 to show the details. The apparatus consists of a slider-crank mechanism converting rotational motion to linear motion, a loading mechanism providing the contact pressure, and the specimens including the plate and the pin. The plate is mounted on the slider, which reciprocates along the guide rail with the rotation of the crank. The crank is driven by a motor, whose revolving speed and angular displacement are precisely controlled by a computer. The pin is held stationary by the pin holder, which is attached to the friction force sensor through a joint bearing, so that the contact surface of the pin self-aligns to the plate to some degree. A normal load, adjusted by weight, is applied on the contact surface through a loading arm. The rolling bearing is used to reduce the influence of loading mechanism on the measured friction force. The friction coefficient is calculated by dividing the friction force by the normal force.

2.2. Test samples and conditions

The material of the pin is AISI 1566 steel with the hardness of 280 HB and the yield strength of 784 MPa. The material of the plate is AISI 1045 steel with the hardness of 194 HB and the yield strength of 355 MPa. The cylindrical pin has a dimension of 15 mm in diameter, thus the nominal contact area is 177 mm^2. The initial surface roughness parameters of pin are R_a=0.12 μm, R_p=0.43 μm, R_v=0.32 μm, and the initial roughness parameters of plate are R_a=1.06 μm, R_p=2.25 μm and R_v=2.58 μm. Before testing, all samples are carefully cleaned with acetone.

Four tests are carried out under different contact pressures and sliding velocities, which are listed in Table 1. Note that sliding velocity is the average velocity of reciprocal motion in this paper, because the instantaneous velocity varies with the crank angle for a slider-crank mechanism. The average velocity is determined by the revolving speed of crank and the reciprocating length which is set as 30 mm for all the tests. The friction pair is lubricated with the oil of SAE 30, whose density, pour point, kinematic viscosity and viscosity index are 885 kg/mm^3, −18 °C, 94 mm^2/s and 100 (at the temperature of 40 °C), respectively. Prior to each test, the lubricating oil with the volume of 1 ml is added to the sliding contact zone.

2.3. Data sampling method

During the whole friction process, the friction force signal is acquired by a data acquisition system with 12-bit resolution. In the slider-crank mechanism, the velocity of the slider varies sinusoidally, which leads to a variation of friction force with the crank angle.

Table 1
Experimental conditions and sampling frequencies.

Test reference	Normal load (N)	Normal pressure (MPa)	Rotation speed of crank (r/min)	Reciprocating frequency (Hz)	Average sliding velocity (m/s)	Sampling frequency (Hz)
1	190	1.07	90	1.50	0.09	18
2	220	1.24	110	1.83	0.11	22
3	250	1.41	130	2.17	0.13	26
4	280	1.58	150	2.50	0.15	30