Tribology International 97 (2016) 77–88

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Experimental observation of cross correlation between tangential friction vibration and normal friction vibration in a running-in process

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A R T I C L E I N F O

Article history:
Received 29 July 2015
Received in revised form
4 January 2016
Accepted 7 January 2016
Available online 15 January 2016

Keywords:
Frictional vibration
Time-frequency features
Cross correlation coefficient
Chaos attractors

A B S T R A C T

Running-in wear experiments were conducted on a spherical-on-disk tester. Cross correlation between tangential friction vibration and normal friction vibration were studied by time-frequency features and cross correlation coefficient. Variations of tangential friction vibration and normal friction vibration were analyzed by chaos attractors. Experimental results show that the cross correlation is poor in the beginning stage, while two signals are significant correlation when running-in continues and high correlation when reaching the running-in. Variation of cross correlation coefficient which could be used to describe the change of wear states in the running-in process is opposite to the change of friction coefficient. Chaotic attractors of two signals converge as running-in go on and can be used to describe variations in the running-in process.

1. Introduction

It is well known that friction vibration originates from the wear process of the tribological pairs. The friction vibration can provide information about the features and wear states of the tribological system. Compared with friction coefficients, worn surfaces and wear debris, both the tangential and the normal friction vibration signal can be easily acquired online simultaneously, and are not be influenced by the operating process. After Thomas first investigated frictional vibration in 1930, many tribology scientists carried on the thorough research for years and contributed much to the development of frictional vibration from the aspects of mechanism and influence factors to mathematical models [1]. When Spurr researched brake squeal on brake assemblies, it was found that friction vibration could be excited in small-scale apparatus [2]. Toistoi discovered frictional self-excited vibrations, which was closely associated with the freedom of normal displacements of a slider [3]. Hunt and Cigan observed a minimum amplitude area of frictional vibration at a special sliding speed [1]. These vibrations were only seen in the up stroke and they could be measured via a reciprocating sliding wear tester. The friction coefficient and sliding velocity were found to affect the friction vibration [4,5]. Graf et al. discovered the system was unstable with the positive friction–velocity-characteristic by friction vibration and dynamic friction laws [6]. Wang et al. found the groove-textured surface could disturb the self-excited vibration of the friction system, and finally significantly reduced the friction noise [7]. Li discussed the effects of system parameters on friction vibration, for example, rigidity, load, lubricant viscosity, surface topography, parameter γ, etc. [8] Researchers established large numbers of models and methods when they studied friction vibration in different fields, for example, a control system [9], aircraft brake whirls [10,11], a violin string [12], a single point sliding system [13,14], wheel/rail interaction [15], groove ball bearings [16], beam contacts [17,18], a ball-screw machine [19], the clutch [20], joints [21–24], etc.

The measurements and researches of friction vibration were mainly focused on the normal direction by some testing apparatus in early years [1] and the studies of the tangential friction vibration were barely mentioned. The scholars did not discuss the modal coupling between normal and tangential vibrations until the 1980s, which could replace the negative friction–velocity slope mechanism and developed a main theory behind squeal generation in the research of friction-induced noise [25]. However, the understanding of excitation mechanisms of squeal still were limited. Chen et al. researched the cross correlation by the modal coupling, then found out that tangential vibration and normal friction vibration were caused by the change of normal force in the analysis of time-frequency and vibration modes without lubrication [25,26]. Unfortunately, few have been done to research the

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http://dx.doi.org/10.1016/j.triboint.2016.01.018
0301-679X/

cross correlation of the tangential friction vibration and the normal friction vibration with lubrication in the running-in process.

In this report, the cross correlation of the tangential friction vibration and the normal friction vibration with lubrication were studied utilizing time-frequency features and the cross correlation coefficient. The analysis of the variation of wear states was carried by cross correlation coefficient, observed by the worn surface of the disk specimen and reflected by the friction coefficient. The variations of the tangential friction vibration and the normal friction were analyzed with chaotic attractors in the running-in process.

2. Experiments

2.1. Apparatus

Running-in wear experiments were conducted on a CFT-I wear tester which is shown in Fig. 1. The friction moment was measured by the sensor of the tester and recorded in the form of friction coefficients. A triaxial acceleration sensor, fixed under the disk specimen (model 356A16 ICP, PCB PIEZOTRONICS Company) with a sensitivity of 100 mv/g and a range of ± 50 g, was used to measure the tangential friction vibration and the normal friction vibration. A data acquisition system (PXIe-1071, NI Company) was used to collect the data at 0.039 ms for a total of 0.159744 s. A set of time sequences signals of the tangential and the normal friction vibrations were collected in every 1 min. An OLS4000 Laser Confocal Scanning Microscope was also used to analyze the surface topography and measure the surface roughness of the tribological pairs in the running-in stage.

2.2. Tribological pair

A spherical-disk specimen was used as tribological pairs in this experiment. The spherical specimen was made of 100Cr6 (ISO 683/17) hardened steel ball with a 830 HV hardness and Ø3 mm diameter. Its chemical compositions (mass, %) were 1.01C, 0.32Si, 0.38Mn, 1.61Cr, 0.08Mo, 0.015P, 0.012S, 0.20Ni, 0.23Cu and the balance Fe. The disk specimen was constructed from a high entropy alloy with a diameter of 30 mm and a thickness of 10 mm, it had a 650 HV hardness and was made of Al, Co, Cr, Fe and Ni.

2.3. Methods

The experiments were conducted under ambient conditions (293 K, 45% relative humidity). On the bench of the wear tester, the spherical specimen was fixed by a special jig. On the bench alongside the spherical specimen, the disc specimen was fixed firmly and driven by a motor, which converted the rotational motion to reciprocating motion.

The electric motor drove the disc specimen at a speed of 600 rpm with a moving distance of 5 mm. The spherical specimen and the disc slid at a calculated relative sliding velocity of 0.1 m/s. Hydrodynamic lubrication was conducted by CD40 (a common marine lube oil) with a density of 0.8957 g/cm^3, a viscosity of 139.6cSt at 40 °C and 12.5 cSt at100 °C. A spring loading system was utilized to apply a test load of 120 N to the disc specimen resulting in a contact pressure between the spherical specimen and the disc specimen of 20.65 MPa.

3. Cross correlation method

In signal processing, cross-correlation is a measure of similarity of two series as a function of the lag of one group of signal relative to another. In time series analysis applied in signal processing, the cross correlation between two time series can be characterized by cross correlation coefficient. The cross correlation coefficient is a statistical concept, which helps describing the degree of relationship between two variables. Its value always lies between -1 to $+1$. If the value of the correlation coefficient is positive, it will indicate the similar and identical relation between the two values, whereas a negative value indicates the dissimilarity between the two values [27]. The cross correlation coefficient is useful for determining the time delay between two signals, and the maximum (or minimum if the signals are negatively correlated) of the cross correlation coefficient indicates the point in time where the signals are best aligned.

In a two dimensional plot, the variables can be arbitrarily labeled as x and y, cross correlation coefficient γ can be calculated

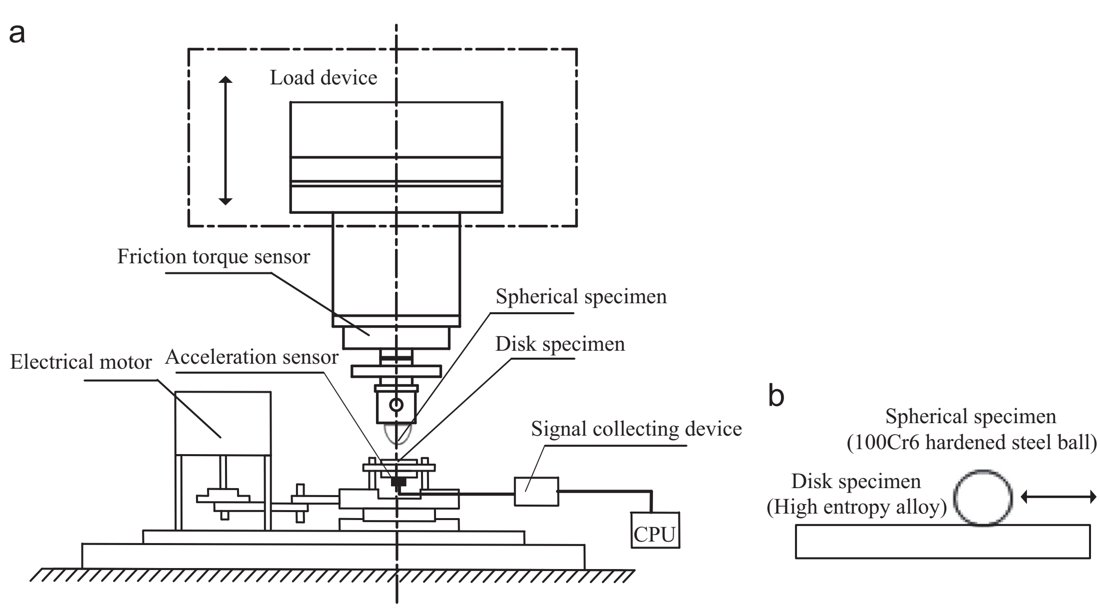

Fig. 1. Schematic diagram of CFT-I wear tester. (a) Experiment device and (b) tribological pair.