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Tribological assessment of sliding pairs under damped harmonic excitation loading based on on-line monitoring methods

Wei Yuan [a,b], Guangneng Dong [a,*], K.S. Chin [b,**], Meng Hua [c]

[a] Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Xi'an 710049, China
[b] Department of Systems Engineering and Engineering Management, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong, China
[c] Department of Mechanical and Biomedical Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong, China

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ABSTRACT

Tribological properties of the working surfaces under damped harmonic excitation (DHE) loading are experimentally evaluated. Tribological tests under DHE loading produced by a spring-connecting weight system were capable to monitor friction with a force sensor and to analyze wear processes by an on-line visual ferrography system, respectively. Effects of different spring-connecting loads and various excitation intervals on the tribological behavior were investigated. Results indicated the existence of an appropriate spring-connecting load to give low coefficient of friction. High excitation frequency could help to accelerate the early completion of running-in process, but long excitation intervals could aggravate wear rate in the running-in period. Main surface damages or wear modes were identified as the consequence of fatigue, side flow, and plowing to generate grooves under various DHE loadings.

1. Introduction

Most operations of mechanical systems may involve with being subjected to dynamic loadings like vibration, and some kind of periodic and randomly oscillating loads. Oscillating loads may directly impact on the surface of mating part to cause severe deformation on the peaks of asperities, which subsequently causes fracturing wear or severely local damage. With sliding between two operating parts taking place, interfacial friction is thus initiated and its magnitude varies depending upon the interaction of the impacting and impacted surfaces. High impact energies may result in severe plastic deformation of microstructure of the surface and subsurface and shear bands in the highly deformed regions [1]. Consequently, crack may initiate and propagate within the subsurface along the shear bands and eventually flake-like wear fragments are detached when these cracks reach the surface, which would subsequently result in catastrophic failure of the mechanical systems. Depending on the impact force and the relative material hardness of the impacted surface, localized and/or repetitive impact tends to create a certain level of local indentation, which may facilitate the damages of fatigue cracking, chipping, peeling and material transfer [2]. Under oscillating loading the impacting surface slides relatively toward the impacted spot on the surface with indentation, the impact body may not be quick enough to retrieve from the indentation completely during sliding. Material of impacted surface in front of the impact body may thus be shorn/plowed off. Due to its gradually retrieving up from the bottom of indentation, the shorn off trace tends to be climbing from the indentation bottom along an inclined shear plane to the top surface of impacted part. This subsequently forms a gradient wear trace to be tilting upwards. In the initial impact, the impacting body inclines to penetrate into the impacted part and deepen the indentation while sliding, which subsequently shears/plows off its immediately upstream material downwardly. The complete cycle of indenting and retrieving is thus likely to result in V-shaped groove-like features to be horizontally dilated along the wear trace so as to form uneven morphology on the impacted surface. Such mechanism thus leads to instantaneously rapid increase of friction.

Automobiles, for instance, often suffer impact loadings while running. Under the seriously running condition, fatal faults are likely to occur with the automobile systems. In addition, it may apt to riding discomfort and driving safety problem. To improve riding comfort and driving safety, the impact with large energy has to be transformed into multiple impacts with small energy and then damped by shock absorbers [3,4]. Thus, the process of shock

* Corresponding author at: Theory of Lubrication and Bearing Institute, Xi'an Jiaotong University, Xian, Shaanxi, 710049, PRC. Mob:13630225881; fax: 029 83237910.
** Corresponding author at: Department of Systems Engineering and Engineering Management, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong, PR China.
E-mail addresses: donggn@mail.xjtu.edu.cn (G. Dong), mekschin@cityu.edu.hk (K.S. Chin).
URL: http://gr.xjtu.edu.cn/web/donggn. (G. Dong).

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absorption can be considered as damped harmonic excitation (DHE) loading. Implementation of thrusting washers in automobiles is common practice in car industries. The influence of DHE loading on the friction and wear of kinematic pairs such as differential gear system on these thrusting washers is still rather lacking and thus deserves.

Available literature indicated that, the tribological properties of various contact surfaces were analyzed under dynamic loading modes. Typically, result of Ewins et al.'s study [5] suggested that the response levels of resonance of different sources under dynamic loading could be 100 or 1000 times greater than the levels resulting from static loading of the same magnitude. Investigation of Iyer and Mall [6] demonstrated that the effect of the high-cycle and low-cycle fatigue components of the load spectrum on the fretting fatigue life normally involved with the contact of flat and cylindrical titanium alloy Ti–6Al–4V surfaces under two-level block loading. Through a series of numerical and experimental results, Haile et al. [7] were able to predict the fatigue life of a rotorcraft structural component subjected to flight load oscillation frequency. Nature and/or type of loading affected friction and wear between two sliding and mating surface, study of Saikko and Kostamo [8] found that, for a pair of similar mechanical system, wear under random loading condition could be 23% higher than its counterpart under static load. Yoon et al. [9] evaluated the frictional characteristics of a pin-on-disc apparatus under fluctuating/vibrating normal force caused by the irregularities of disk surface.

Vibration control systems are rather complex. Their effective structural design usually has to integrate several hardware and software technologies, together with smart materials, adaptive dampers, actuators, sensors, and control and signal processing algorithms [10]. Building up of such systems is rather time consuming and costly if it is merely for experimental purpose. Ferrography is a commonly used wear monitoring technique in various modern industries and academic researches. A typical on-line visual ferrograph (OLVF) system was developed based on magnetic deposition and image analysis, and an index of particle coverage area (IPCA) and full binary image division were proposed so as to provide meaningful quantitative parameters [11,12]. The developed OLVF system was used by Cao et al. [13] to monitor the in-situ real variation of wear in a mechanical system with relative movement between piston rings and cylinder liners under stepped loading. Results of their study effectively verified the effectiveness of using OLVF system to identify near failure of a sliding mechanical system. Based on wear information or data obtained via OLVF, Zhang et al. [14] proposed a linear threshold value method to determine the running condition of engines, as ad-hoc function to enhance OLVF capability. Further embedding a wavelet-analysis-based differential method specifically for data analysis improved the reliability of OLVF in monitoring the tests of engine wear and in identifying the in-situ wear condition [15]. Through different studies of the wear behaviors of dissimilarly sliding mechanical systems using OLVF, it suggests such improved OLVF to be adequately applied to monitor the in-situ wear condition.

Hence, our study involved with the selection of simplified DHE loading which was applied onto a frictional sliding pair mounted in a ball-on-disc test rig, and used (i) on-line monitoring approaches to determine the relative friction and (ii) OLVF to monitor wear behaviors. The investigations aimed at exploring the tribological properties of friction pairs that slide under the loading mode of DHE. The DHE loading mode was generated simply by exciting a spring-connecting load which consisted of a spring between weights and a lever. The coefficient of friction (COF) was subsequently calculated by the value on the envelope of DHE loading curves and its corresponding value of friction force on friction force curves. A force sensor was used and OLVF system to monitor friction force while OLVF system was used to assess wear processes during experimental studies. In addition, a TR200 profilometer and a scanning electron microscope (SEM) were used to analyze the cross-sectional profile and morphology, respectively, of the wear tracks.

2. OLVF monitoring system and IPCA

The on-line visual ferrograph (OLVF) system [13] has specifically been developed and currently used in wear particle monitoring of some gearboxes and engines [15,16]. The development of the technique provides means for high-frequency on-line sampling and analyzing wear-particles to replace the inefficient and time consuming off-line analytical approaches. The OLVF system (Fig. 1) integrates an oil sampling system, a magnetic coil control system with a semiconductor image sensor and a personal

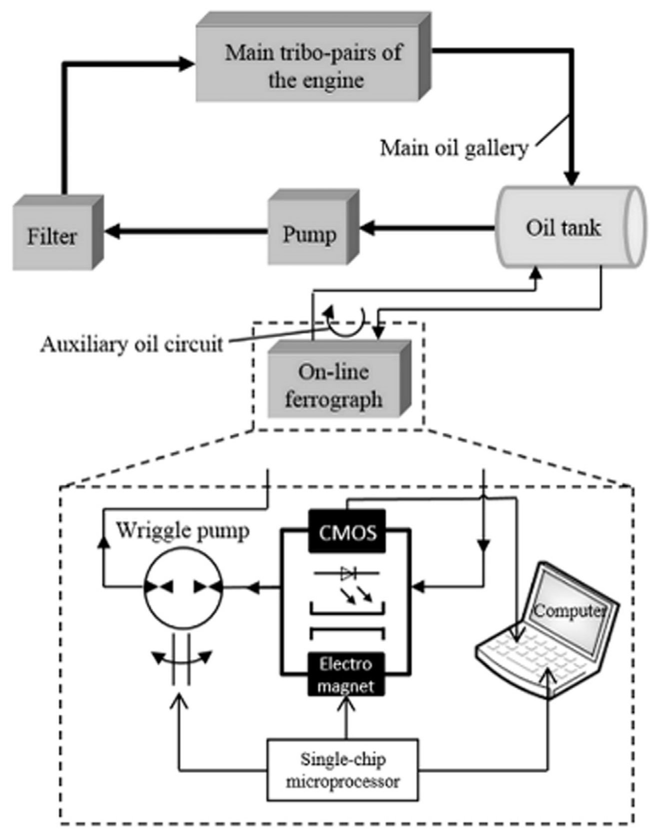

Fig. 1. Diagram of the OLVF system.

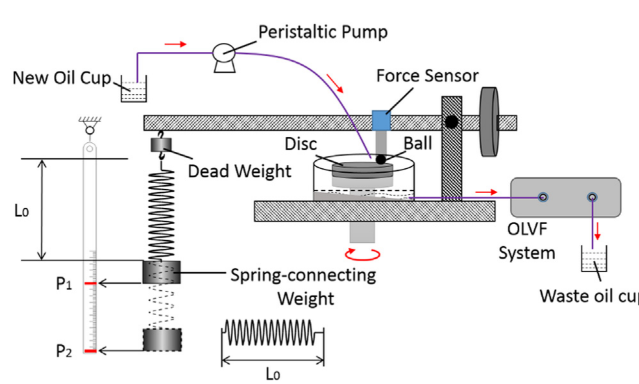

Fig. 2. Schematic of ball-on-disc rig.