Experimental Study of the Variation of Friction Vibration in the Running-in Process with Different Sliding Velocity

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Abstract. The variation of friction vibration in the running-in process with different sliding velocity was studied. Experiment shows that friction vibration varies with the change of sliding velocity. Friction vibration gradually increases in the whole running-in process under 300r/min, is increasing then smooth and stable fluctuant under 400r/min and 500r/min, is growing larger then fluctuant to stable under 600r/min and the inflection point of 400r/min, 500r/min and 600r/min are 50min, 40min and 30min, respectively. However, friction vibration is least under 400r/min, but not under 300r/min, and largest under highest sliding velocity 600r/min. Therefore, sliding velocity affects the running-in process and friction vibration could be used to monitor and identify the surface asperity contact of worn surface when sliding velocity changes.

Introduction

Sliding velocity is one of the most important properties which affect friction and wear state of tribological pairs in a running-in process. Many tribology researchers had proved this idea and observed a series of phenomenon by model, mechanism, experiment, etc. Vollebregt et al. studied the influence of a velocity-dependent friction law on the interactions inside the contact patch between a rolling wheel and a rail [1]. Shafiei et al. proposed a modified Archard equation to predict wear rates of nanocrystalline Ni as a function of grain size and sliding speed [2]. Tamai et al. established a nonlinear friction coefficient model included contact pressure, sliding velocity and sliding length to improve the accuracy of predictions of the formability of steel sheets [3]. Stembalski et al. presented a method to determine the coefficient of friction with consideration of sliding speed and normal pressure for steel C45 and steel 40HM [4]. Cui et al. investigated the lubricated diamond-like carbon (DLC) films to study the primary low-friction mechanism of DLC [5]. Ma et al. studied sliding tribological behaviors and wear mechanism of Cu-graphite composite against different counter parts at different speeds [6]. Asadi Kouhanjani et al. performed experiments using various sliding velocities to investigated friction and wear behavior of a peak aged Cu-0.65 wt. % Cr alloy [7]. Hiratsuka et al. researched the effects of non-friction time along with sliding velocity by a twin-ring sliding type wear test rig [8]. Ruiz-Andres et al. studied friction and wear rate behavior of dual phase steel discs at different sliding speed under unidirectional ball-on-disc dry sliding conditions [9]. Yanase et al. evaluated effects of sliding velocity on friction at extremely low sliding velocity approximating orthodontic tooth movement and found frictional forces tended to increase as the sliding velocity decreased [10]. Tyagi et al., Kim et al., Miki et al., Yamaguchi et al., Zeng et al., Lodygowski et al., Gu et al., Kakas et al., Gunes et al. and Vadiraj et al. investigated friction and wear behavior of different reibological pairs, and all of them observed a definite reduction in the friction coefficient as the sliding speed increased [11-21].

Friction vibration provides information about the features and wear states of the tribology system, which originates from the wear process of the friction pair. Friction vibration signal could be easily acquired in real-time online, and are not influenced in the operating process. Sliding velocity is one of the most important factor that influence friction and wear state of tribological pair, and a number of tribology scholars have studied the effect of sliding speed by friction coefficient, worn surface, etc.
However, few jobs have been done to study the effect of sliding velocity in the running-in process by friction vibration signals in the published works, as friction vibration is a benefit reflection of friction and wear state of tribological pair, therefore, it is meaningful to research the variations of friction vibration in the running-in process with different sliding velocity.

In this report, 100Cr6 (ISO 683/17) and cast alloy iron were tested as tribological pair, in the beginning of this work, the variation of friction vibration in the running-in process with different sliding velocity was studied by time-frequency feature and mean value of time-domain, then it was compared with the change of friction coefficient and worn surface.

**Experiments**

**Friction Test**

Spherical-on-disk sliding friction and wear experiments in the running-in process under ambient conditions (293K, 45% relative humidity) with lubrication (submerged lubrication with CD40, an ordinary marine lube oil with a density of 0.8957g/cm$^3$, a viscosity of 139.6 cSt at 40°C and 12.5 cSt at100°C) were conducted on a CFT-I tribometer (LKCSTDC, China), as shown in Fig. 1. The spherical specimen was made of 100Cr6(ISO 683/17) hardened steel ball with a 825 HV hardness and Ø3 mm diameter, the chemical compositions (mass, %) of which were 1.01C, 0.32Si, 0.38Mn, 1.61Cr, 0.08Mo, 0.015P, 0.012S, 0.20Ni, 0.23Cu and balanced Fe. The disk specimen was constructed of cast alloy iron with Ø30 mm×10mm with a hardness range from 300-400 HV and the major chemical compositions of disk specimen was Fe, C, Si, Mn and P. A load of 70N was applied to the disc specimen, the test sliding velocities were 300r/min (0.05m/s), 400r/min (0.067m/s), 500r/min (0.083m/s) and 600r/min (0.1m/s), respectively. The tests were repeated four times under the same conditions with various experiment continued to ensure a perfect repeatability.

![Experiment device](image)

Figure 1. Schematic diagram of CFT-I wear tester.

**Methods**

Friction moment was measured by the sensor of the tester and friction coefficient was recorded in the form. A triaxial acceleration sensor (model 356A16 ICP, PCB PIEZOTRONICS Company) with a sensitivity of 100 mv/g and a range of ±50 g fixed under the disk specimen was used to measure normal friction vibration. A data acquisition system (PXIe-1071, NI Company, USA) with the sampling points of 4096 and the sampling interval of 0.039 ms was used to store the data of normal friction vibration signals in every 1 min. The disc sample surface topography and roughness were measured several times by laser scanning confocal microscope (LSCM, OLS4000, Japan) before and after the tests.
Results and Discussion

In order to research the variation of friction vibration in the running-in process with sliding velocity, referenced the methods in [22], through the comparative analysis of reconstructed signals in different frequency bands, it was found out that the reconstructed signals in the range of 2000-3000 Hz show a significant friction vibration and the variation of friction vibration in the running-in process with different sliding velocity was analyzed as follows.

The Variation of Friction Vibration with Different Sliding Velocity

Fig.2 presents waveform and spectrum diagram of friction vibration with the sliding speed of 500r/min in (a) the beginning of running-in, (b) 15min, (c) 30min, (d) 45min and (e) 60min. It can be clearly seen that the amplitude of friction vibration has a trend of increase firstly, then smooth and stable fluctuant as the running-in process goes on.

![Waveform and spectrum diagram of friction vibration in range of 2000-3000Hz of 500r/min.](image)

Figure 2. Waveform and spectrum diagram of friction vibration in range of 2000-3000Hz of 500r/min.

In order to research the variation of friction vibration with different sliding velocity, mean value of absolute value of friction vibration of time domain was calculated, then cubic fitted with 95% confidence bounds, as illustrated in Fig.3. It could be seen in Fig.3 (a), the amplitude of friction vibration under 300r/min continued to increase as time went on in the whole experiment process, which indicated the running-in process was not over within 60min. Seen in Fig.3 (b)-(d), when sliding velocity were 400r/min, 500r/min and 600r/min, all of amplitudes of friction vibration were increasing, then smooth and stable fluctuated, which indicated the running-in process of tribological pair changed from the running-in beginning to the running-in state-the whole running-in was over. But the stable fluctuant time of different running-in process with different sliding velocity were variable, was around 50 min under 400r/min, nearly 40 min under 500r/min and approximate 30 min under 600r/min. The prediction of the running-in process with different sliding velocity based on friction vibration was consistent with the analysis results of the friction coefficient. Fig.4 shows the variation of friction coefficient during the running-in process with different sliding velocity (cubic fit,
with 95% confidence bounds). Seen from Fig. 4, when sliding velocity was 300r/min, the friction coefficient continued to increase in the whole running-in process, as shown in Fig.4 (a). Seen in Fig.4 (b)-(d), when sliding velocity is 400r/min, 500r/min and 600r/min, the friction coefficient was increasing, then smooth and stable fluctuated. The stable fluctuant time of 400r/min, 500r/min and 600r/min were also nearly 50min, 40min and 30min, respectively. However, comparing with different running-in process, which is generated by different sliding velocity, the variation of friction vibration is different with the change of friction coefficient. It could be observed in Fig.3 (a)-(d), friction vibration is least under 400r/min, but not under the lowest sliding velocity 300r/min, larger under 500r/min and largest under the highest sliding velocity 600r/min. However, the friction coefficient is largest under the lowest sliding velocity 300r/min, lesser under 400r/min, even lesser under 500r/min and least under the highest sliding velocity 600r/min, as illustrated in Fig.4 (a)-(d). The reason of the variations are discussed below.

The Discussion of the Variation of Friction Vibration under Different Sliding Velocity

The increase of sliding velocity is benefit for the formation of interoperable worn surface of tribological pair, hence, the running-in process gets shorten when sliding velocity increases, which is consistent with the results presented above. However, the amplitude of friction vibration is least under 400r/min, which indicates the surface asperity contact of worn surface is the best, but the amplitude of friction vibration is large under 300r/min and 500r/min, which demonstrates the surface asperity contact of worn surface was worse than it is under 400r/min, and the amplitude of friction vibration is the largest under 600r/min, which indicates surface asperity contact of worn surface is the worst. Therefore, the friction vibration could reflect surface asperity contact of worn surface of tribological pair, but the friction coefficient could not reflect surface asperity contact of worn surface of tribological pair. The analysis is detailed as follows.

The Friction Coefficient. According to reference [23], the variation of friction coefficient is attributed to the increase of quantity and range of metallic oxides, which are benefit grinding agents and lower friction due to the temperature rise sharply of tribological pair when sliding speed increases. Fig.5 presents worn surface micrographs of disc specimen after experiment with different sliding velocity. It can be seen that the quantity and region of metallic oxides (mainly the black parts circled in yellow in Fig.5) are different when sliding velocity changes. There is only a little part of metallic oxides under 300r/min, as shown in Fig.5 (a). When sliding velocity are 400r/min, 500r/min and 600r/min, the quantity and region of metallic oxides are increasing with the increase of sliding velocity, as illustrated in Fig.5 (b)-(d). Therefore, friction coefficient decreases when sliding velocity increases, as shown in Fig.4. However, worn surface roughness which is a reflection of the contact state of worn surface after experiment is neither increasing nor decreasing with the increase of sliding velocity.
velocity. For example, when sliding velocity is 600r/min, worn surface roughness of disc specimen after experiment reaches to 0.925µm and the largest, worn surface roughness of disc specimen after experiment is 0.43µm and the least under 400r/min, but not under the lowest sliding velocity 300r/min. Hence, friction coefficient could not reflect the surface asperity contact of worn surface in the running-in process.

The Friction Vibration. The variation of friction vibration is attributed to the change of surface asperity contact. When worn surface is rough, the surface asperity contact changes violently. Hence, the friction vibration excited by the micro convex bodies collision is so violent, and its amplitude is high. On the contrary, the friction vibration is weak, and its amplitude is low. The surface asperity contact of worn surface are different when sliding velocity changes. When sliding velocity was 300r/min, surface roughness after experiment was 0.517µm and the worn surface was fairly rough, the surface asperity contacted violently. Hence, the amplitude of friction vibration was a little large and fluctuant increased, as shown in Fig.3 (a). When sliding velocity was 400r/min, surface roughness after experiment was 0.43µm and the surface asperity contact of worn surface after experiment was better than 300r/min, the surface asperity contacted slightly than it was under 300r/min and the amplitude of friction vibration was lesser than it was under 300r/min, as presented in Fig.3 (b). When sliding speed was 500r/min, the worn surface roughness after experiment was 0.538µm and the disc specimen surface was worse than it was 400r/min, the surface asperity contacted more violent than 400r/min and the amplitude of friction vibration was larger than before, as illustrated in Fig.3 (c). When sliding velocity was 600r/min, worn surface roughness after experiment reached to 0.925µm and the largest, the worn surface after experiment was roughest, the surface asperity contacted even more severe and the amplitude of friction vibration got its largest, as shown in Fig.3 (d).

As discussed above, sliding velocity affects the friction and wear state of tribological pair in the running-in process. When the sliding velocity is high, the running-in time gets short. On the contrary, the running-in time is long when under low sliding velocity. Both friction vibration and friction coefficient could be used to identify the running-in process. However, the worn surface roughness after experiment is various when sliding velocity changes. The worn surface roughness after experiment is least when sliding velocity is 400r/min, larger under 300r/min and 500r/min, largest under 600r/min. But the variation of friction coefficient is different with the change of worn surface roughness, when sliding velocity is high, the metallic oxides are large and the friction coefficient is low. Hence, friction vibration could be used to monitor and identify the surface asperity contact of worn surface of tribological pair with different sliding velocity in the running-in process, but friction coefficient could not reflect surface asperity contact of worn surface of tribological pair with different sliding velocity in the running-in process.

Conclusion

The friction vibration signal can be used to depict the running-in wear state of the friction pair with different sliding velocity. In this report, 100Cr6 (ISO 683/17) and cast alloy iron were tested as tribological pair, in the beginning of this work, the variation of friction vibration in the running-in process with different sliding velocity was studied by time-frequency feature and mean value of time-domain, then it was compared with the change of friction coefficient and worn surface. From the presented results, it can be concluded as follows:

(1) Sliding velocity affects the friction and wear state of tribological pair in the running-in process. The running-in process gets shorten when sliding velocity increases, but the surface asperity contact of worn surface is best under 400r/min, more worse under 300r/min and 500r/min, the worst under 600r/min.

(2) The amplitude of friction vibration is least under 400r/min, but not under the lowest sliding velocity 300r/min, larger under 500r/min, largest under highest sliding velocity 600r/min and friction vibration could be used to monitor and identify surface asperity contact of worn surface of tribological pair with different sliding velocity in the running-in process.
(3) The change of friction coefficient is different with the variation of worn surface roughness after experiment, unlike friction vibration, friction coefficient could not reflect surface asperity contact of worn surface of tribological pair with different sliding velocity in the running-in process.

References


