

Lubricated Friction and Wear Properties of P-B Bearing Flaky Graphite Cast Iron

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Keywords: Tribology, Frequency, Stroke, Cylinder liner, Separation voltage, Surface roughness

Abstract. Lubricated reciprocating tests were conducted on an SRV tester to investigate effects of stroke and frequency on frictional and wear properties of flaky graphite cast iron used for marine cylinder liner by varying frequency and stroke under a given sliding velocity in boundary and mixed lubrication regime. It was clarified that changes in coefficient of friction were significantly dependent on stroke and frequency: in boundary lubrication, coefficient of friction at steady state showed a lower value at a combination of lower frequency and therefore larger stroke. In mixed lubrication, however, a combination of lower frequency and larger stroke produced a higher friction. In boundary lubrication where no run-in process was observed, higher frequency contributed to producing rougher surfaces resulting in higher friction. In mixed lubrication bordering on boundary lubrication higher frequency promoted run-in, enhancing film formation and lowering friction. Effects of frequency and stroke also reflected on wear, changes in separation voltage between a disk and a ball specimen, which were in accordance with changes in friction.

Introduction

Marine cylinder liner materials are investigated in terms of microstructure, surface topography, lubricity etc. to perform minimum friction and wear to meet increasing demands on reducing pollution and fuel costs [1-5]. Many of investigations were conducted under reciprocating sliding because of their applications. It is quite often, however, that experimental backdrops of selecting specific frequency and stroke are left unclear.

In reciprocating contacts which are subjected to non-steady sliding velocity, changes in frequency and stroke under a given sliding velocity should have different respective effects on oxide film and oil film formation. It was clarified that not only frictional and wear properties but also effects of EP (Extreme Pressure) additives were influenced by frequency and stroke [6]. It is also pointed out that oil film thickness at an acceleration and deceleration stage during one stroke were different from each other [7-8], demanding the need for newly building up EHL (Elastohydrodynamic Lubrication) theory as the present EHL theory is based on steady sliding velocity.

In this report, effects of frequency and stroke on friction and wear of marine cylinder liner materials with different surface finish were studied by measuring separation voltage and frictional waves in boundary and mixed lubrication. It was made clear how friction and wear in boundary and mixed lubrication were influenced by frequency and stroke.

Experimental Procedure

Fig.1 shows microstructure of 3.2t-marine-cylinder-liner casting, in which graphite flakes are embedded in pearlite matrix with steadite, and chemical composition of cylinder liner is shown in Table 1. Schematic of Optimol SRV tester is shown by Fig.2. For an upper oscillating specimen, an SUJ2 bearing steel ball of 10 mm in diameter was used. For a lower fixed disk, specimens were cut out of marine cylinder liner bars cast by sand mold into a dimension of 24mm in diameter and 7mm in thickness with two different surface roughness, buff (Ra 0.12μm) and ground (Ra 2.32μm) finish.

Three base paraffin oils with different viscosity, H60 ($8.19\text{mm}^2/\text{s}$ @313K), H500 ($86.65\text{mm}^2/\text{s}$ @313K) and BS ($383\text{mm}^2/\text{s}$ @313K) were used as lubricants. An oil bath (0.5ml) was made with a stainless ring attached to a disk.

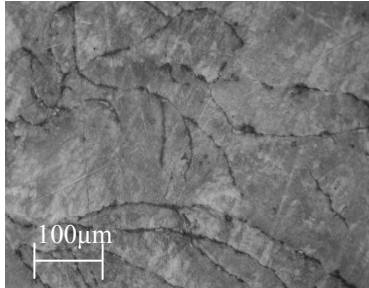


Fig. 1. Photomicrograph of cylinder liner.

Sliding velocity ranged from 0.06m/s to 0.16m/s with application of 60N, 90N and 110N. An upper and a lower specimen were insulated by mica from a body of the tester to measure the separation voltage between specimens. The separation voltage circuit consisted of direct and parallel resistance with application of a dry battery cell 1.5V. The ratio of direct resistance to parallel one was chosen as 14:1, so that separation voltage may show 100mV for maximum voltage. Detection of oxide film in boundary lubrication and oil film formation in mixed lubrication is possible by switching to $22\ \Omega$ for boundary and $5.2\ \text{k}\Omega$ for mixed lubrication respectively. Wear volume was determined by the product of a stroke length and cross section perpendicular to a sliding direction. A cross section of a worn track was computed from surface profiles measured at three locations, stroke middle and two other locations between stroke middle and ends.

As is shown below, average sliding velocity V_{mean} is represented by $2 \times f \times s$ in Eq.3, where f stands for frequency [Hz], s for stroke [mm], ω for angular velocity [rad /s], t for time [sec], and y for position [mm]. In this experiment, stroke 1.0 mm and 2.5 mm were chosen for each of 0.06 m/s and 0.16 m/s.

$$y = \frac{S}{2} \sin \omega t \quad (1)$$

$$= \frac{S}{2} \sin 2\pi f t$$

$$V = \frac{dy}{dt} = \pi f S \cos 2\pi f t \quad (2)$$

$$V_{\text{mean}} = \pi f^2 S \int_0^{\frac{1}{f}} |\cos 2\pi f t| dt$$

$$= 2 \times f \times S \quad (3)$$

Results and discussion

Frictional Characteristics of Cylinder Liner Materials in Boundary Lubrication. Fig.3 (a) and (b) show changes in friction with time for buff-polished and ground finish under 60N, 90N and 110N slid at 0.06m/s in H60 oil. Significant effects of stroke and frequency on changes in coefficient of friction were observed for both of buff-polished and ground finish. At 2.5mm, changes in coefficient of friction at steady stage were around 0.06 for both of buff-polished and ground finish, whereas those at 1.0mm were distributed between 0.08 and 0.18. Initial friction at 1.0mm rose above 0.25 under 90N for buff-polished and ground finish. For buff-polished and ground finish, the time taken from initial to steady state was longer at 1.0mm than at 2.5 mm.

Table 1 Chemical composition

C	Si	Mn	P	S	B
3.31	1.19	0.68	0.238	0.058	0.024
V	Ti	Cr	Cu	Sn	Pb
0.003	0.017	0.05	1.14	0.027	0.001

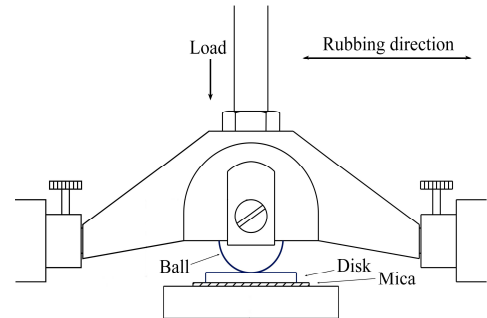


Fig. 2 SRV reciprocating tester

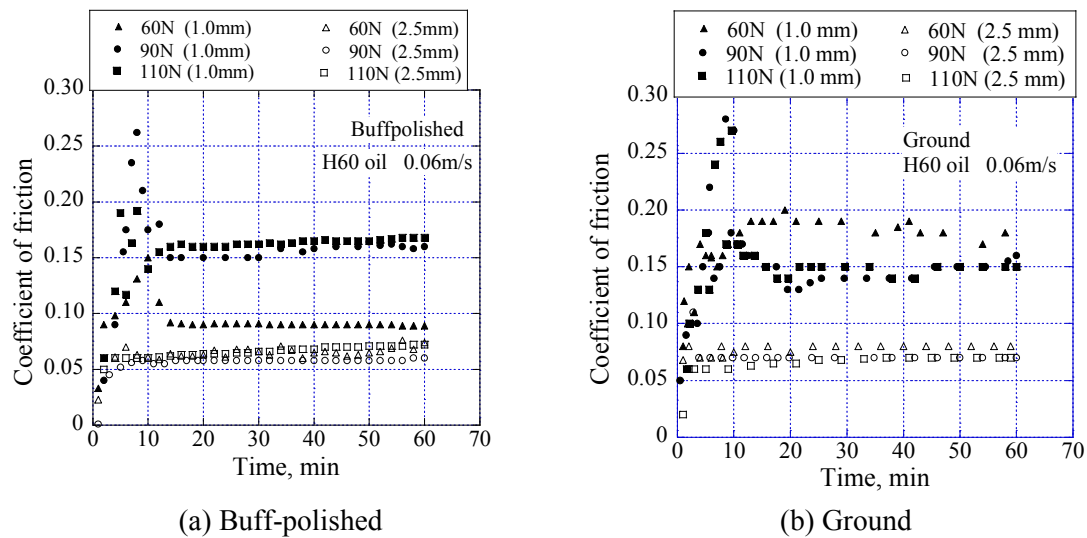


Fig. 3 Effects of stroke length on changes in coefficient of friction with time for buff-polished and ground finish slid at 0.06m/s in H60 under 60N, 90N and 110N.

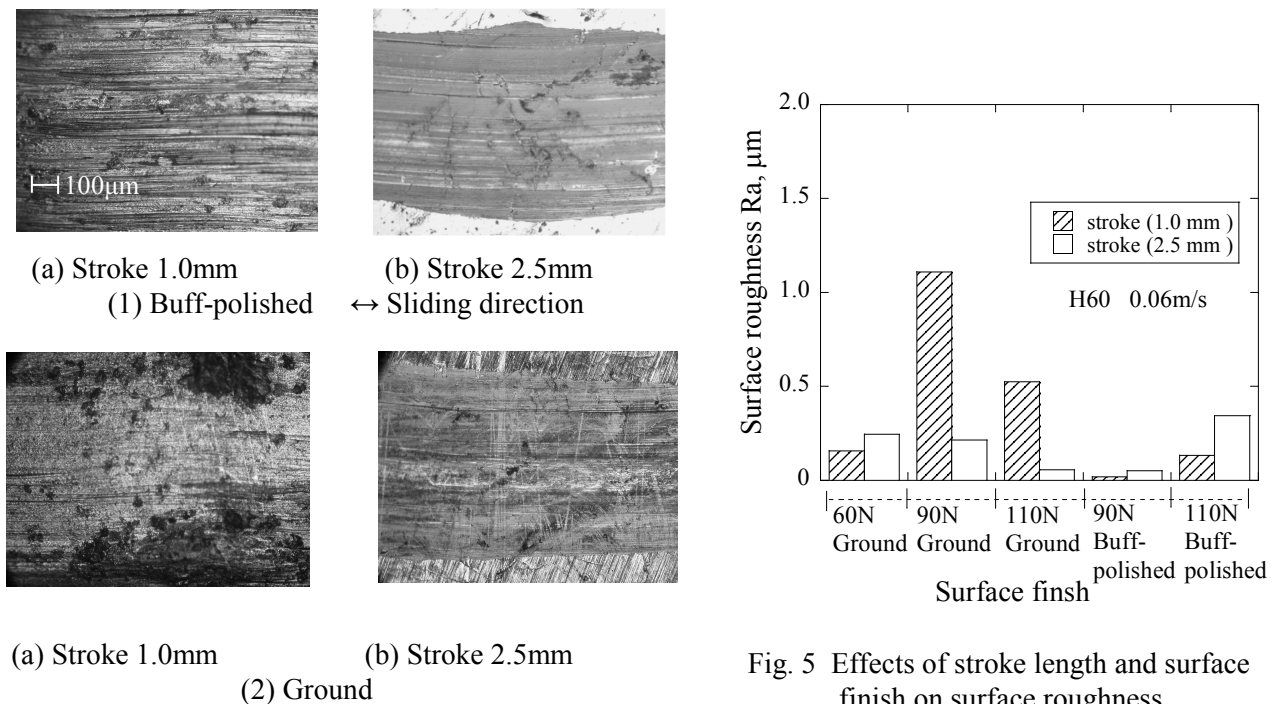


Fig. 5 Effects of stroke length and surface finish on surface roughness.

Fig. 4 Optical micrographs of wear tracks on buff-polished and ground disks under 90N.

Fig.4 (1) and (2) show photomicrographs of worn tracks of buff-polished and ground disks at 1.0 mm and 2.5 mm. Though only few millivolts were detected in separation voltage measurement with parallel resistance 22Ω , observation by optical microscope showed difference of oxide film formation between 1.0 mm and 2.5 mm. Both of worn tracks of a buff-polished and ground disk at 2.5 mm show oxide film formation but ground tracks are still observable on a ground disk worn track. At 1.0 mm, worn tracks of a ground disk exposed less-developed oxide film with metallic luster than buff-polished counterpart at 1.0mm, showing severe abrasion and adhesion compared with those tracks of a buff-polished disk. Oxide film formation increases load-carrying capacity and scuffing resistance [9-10]. Under the same sliding velocity, higher frequency caused larger number of reciprocating contacts between a disk and ball specimen than lower frequency, and increased the

number of turn of reciprocating motion at stroke ends, making it hard to promote run-in process in worsening lubricating conditions. Higher frequency thus produced more rougher surface for ground finish than buff-polished counterpart as is shown in Fig.5, resulting in higher friction because of severe abrasion and adhesion than at lower frequency and therefore longer stroke.

Frictional Characteristics of Cylinder Liner Materials in Mixed Lubrication. Fig.6 shows changes in coefficient of friction with time for buff-polished and ground finish slid at 0.06m/s and 0.16 m/s in BS oil under 20N. At 0.06m/s, coefficient of friction at 2.5mm was lower than that at 1.0 mm for both of buff-polished and ground finish. However, when sliding velocity was increased from 0.06m/s to 0.16 m/s, contrary to changes in coefficient of friction at 0.06 m/s, coefficient of friction turned lower at 1.0mm than at 2.5 mm for both of buff-polished and ground finish. Fig.7 (a) and (b) show frictional waves at 1.0 mm and 2.5 mm for buff-polished slid at 0.16m/s. At 1.0 mm, the frictional waves showed increase in friction at both of stroke ends and drop at the middle of stroke, typical of mixed lubrication. However, friction at an inlet of oil was higher than that at an outlet of oil because of non-steady sliding velocity effect, in which film thickness was larger at an outlet than at an inlet [7-8]. At 2.5 mm, the upper shapes of frictional waves were different from those lower wave shapes, which show difference of lubricating conditions between forward and backward stroke. Non-steady sliding velocity effects as was observed at 1mm were not detected at 2.5mm.

To detect effects of surface finish, frequency and stroke on run-in and oil film formation, separation voltage was measured with parallel resistance 5.2 k Ω . The separation voltage results are shown in Fig.8 (a) and (b). For buff-polished finish, the separation voltage for 1.0 mm was higher than that for 2.5 mm at 0.06 m/s. With raise in sliding velocity from 0.06 m/s to 0.16 m/s, the time at stroke ends became shorter, which made drop in separation voltage less frequent and increased the voltage. It was confirmed that for a bearing steel ball on a mild steel disk, skewness plotted against the number of reciprocating cycles decreased lineally in proportion to increase in the number of reciprocating cycles, or increasing frequency at a given sliding velocity [6]. As run-in is reflected on decrease in skewness [11], it follows that higher frequency promoted run-in and enhanced elastohydrodynamic lubrication effect. Larger voltage for 1.0 mm than that for 2.5mm over 30 min. at 0.16 m/s in Fig.8 (a) could be attributable to promotion of run-in, which was in accordance with the frictional waves in Fig. 7(a). For ground finish, fluctuation in separation voltage was observed at 2.5 mm slid at 0.06 m/s showing less elastohydrodynamic lubrication effect due to poor run-in, repeating collapse and build-up of oil film.

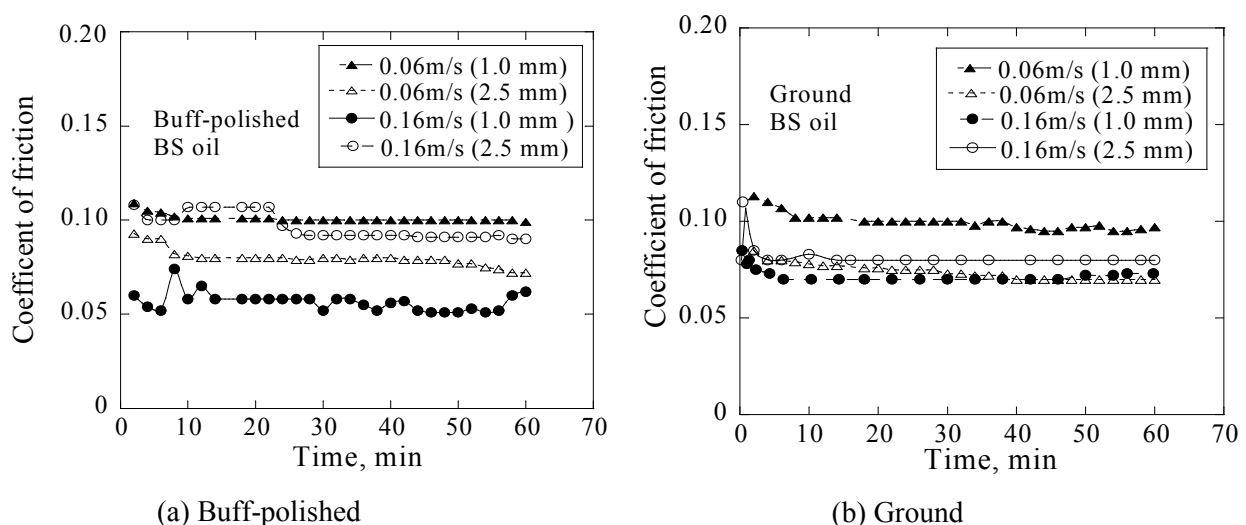


Fig. 6 Changes in coefficient of friction with time for buff-polished and ground finish slid at 0.06m/s and 0.16m/s in BS under 20N.

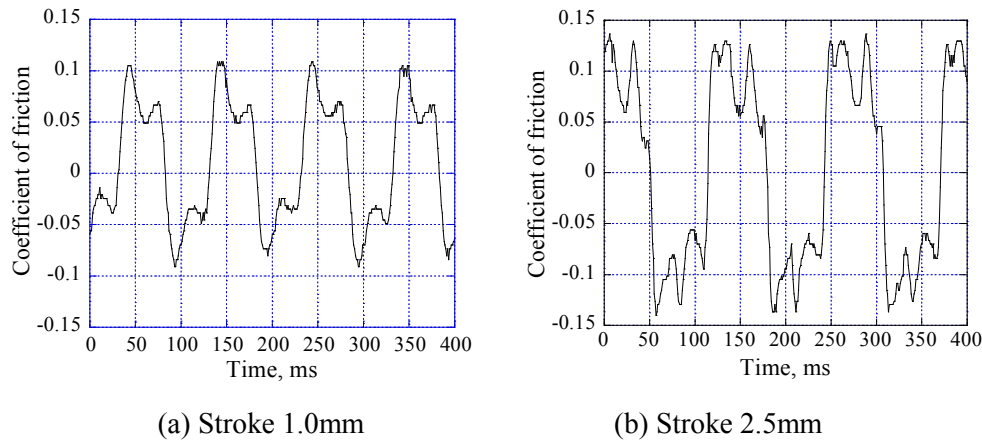


Fig. 7 Effects of stroke on frictional waves for buff-polished finish.

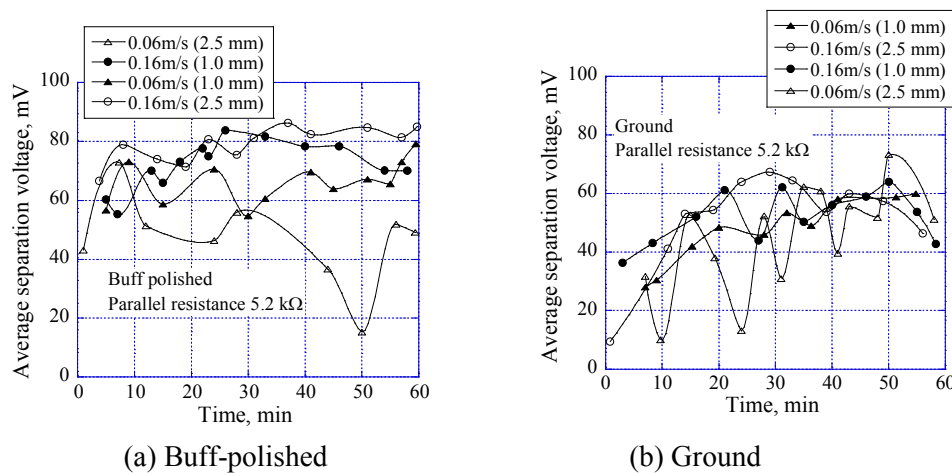


Fig. 8 Effects of surface finish on average separation voltage for buff-polished and ground finish slid at 0.16m/s in BS.

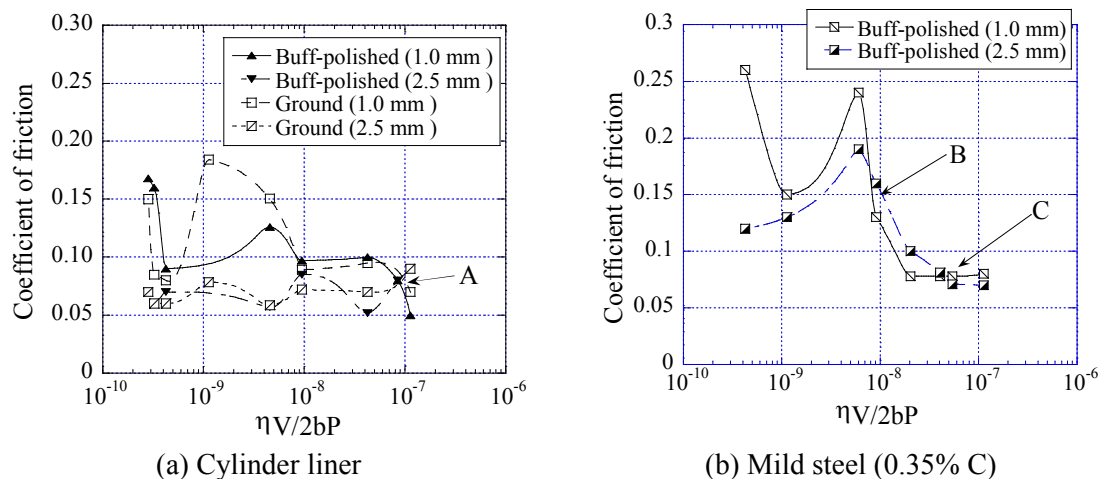


Fig. 9 Changes in coefficient of friction at stroke 1.0 mm and 2.5mm for cylinder liner and mild steel in boundary and mixed lubrication.

Fig.9 (a) shows the relationship between coefficient of friction and $\eta V/2bP$, a non-dimensional bearing characteristics number for cylinder liner and (b) for 0.35% C mild steel for comparison. In $\eta V/2bP$, η stands for viscosity [Pa·s], V for sliding velocity [m/s], P for Hertzian for maximum stress [Pa], $2b$ for Hertzian contact width [mm]. In Fig.9 (a), point A shows where effects of higher frequency and smaller stroke on coefficient of friction turned around for buff-polished and for ground finish. Point A for cylinder liner corresponded to point B for mild steel, though

coefficient of friction for mild steel was higher. Point C for mild steel shows another turnaround where coefficient of friction became lower at a combination of a larger stroke and lower frequency for $\eta V/2bP$ value larger than that corresponding to point C, demonstrating elastohydrodynamic lubrication effects became dominant as mixed lubrication approached fluid lubrication [12].

Fig.10 shows changes in specific wear rate plotted against $\eta V/2bP$. Significant increase in specific wear rate was observed for ground and buff-finish at 1.0 mm below 10^{-9} in $\eta V/2bP$, which coincided with changes in coefficient of friction.

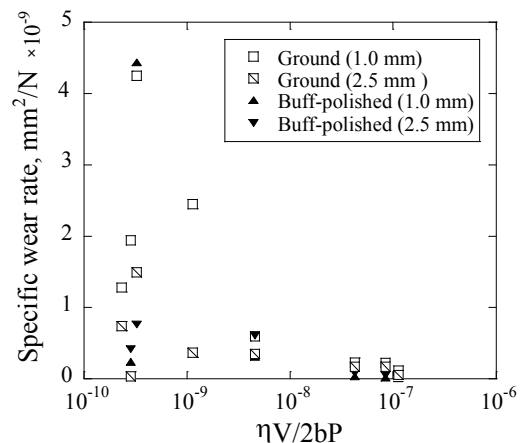


Fig. 10 Effects of stroke and surface roughness on specific wear rate.

Conclusion

Effects of stroke and frequency on reciprocating friction and wear of cylinder liner with different surface finish were studied by varying frequency and stroke under a given sliding velocity in boundary and mixed lubrication. The main results from this study are as follows:

1. There were two regimes in boundary lubrication depending on promotion of run-in. Below 10^{-7} in $\eta V/2bP$, for buff-polished and for ground finish, coefficient of friction was higher at higher frequency and therefore smaller stroke. Above 10^{-7} , run-in was promoted by higher frequency and coefficient of friction showed a lower value at higher frequency and smaller stroke vice versa.
2. In mixed lubrication bordering on boundary lubrication, frictional waves depicted that coefficient of friction for higher frequency was larger at the inlet than that at the outlet, indicating the difference of oil film thickness at acceleration and deceleration stage.

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