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Design and test a load-varying apparatus for wear test device

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ABSTRACT

Contact conditions variation with time challenge the common steady state lubrication characteristic estimations. Wear test devices usually apply a constant load on the contact surfaces. These apparatuses should improve to have the possibility of time variation condition testing. In this study, a load-varying system has been designed to complete the pin-on-disk wear test device. By adding this system, it is possible to change the load with time in different patterns. The intensity of the current passing through a magnetic coil mounted on the load lever is controlled by an electronic control unit to produce instance load. Several tests are designed with 10w40 oil as lubricant in the contact between the pin of 100-chrome-6 bearing steel and the ST37 steel disc. Four different patterns of time-varying load, including ascending, descending, sinusoidal, and ascending-descending patterns are investigated. The results show that the variable load created by the system completely affects the contact friction behavior and the type of load change pattern is effective in the measured friction force. The decrease of friction force is observed in all cases with an increase in the linear speed. It is found that, in a complete cycle the friction coefficient shows a reverse trend with respect to the normal load pattern.
Keywords: Lubrication; elastohydrodynamic; friction; variable load; Magnetic

1. Introduction

Lubrication of mechanical parts is very important because it has a direct effect on reducing friction, wear, energy consumption, and costs. Therefore, investigating the lubricating fluid behavior in real situations is essential for improving the lubrication conditions and also increasing the efficiency. The lubrication conditions such as geometries, entraining speed, applied load, and lubricant composition may not be constant all the time and some of them can change. Therefore, the study on lubrication in a steady state leads us to the estimations that are far from reality. In order to improve the models, all the variables or a part of them should be considered in the study in a variable form with respect to time.

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One of the clear examples of the time-varying contact problem occurs in lubricated gears. The load is constant until only one pair of teeth supports the entire load. By engaging two pairs of teeth, the load is reduced from two-thirds to one-third. Several studies presented a transient elastohydrodynamic lubrication analysis for gears [1-6]. Another field of application is variable load lubrication of artificial joints. Considerable studies try to derive a transient lubrication model for the joint [7-10]. These models simulate all the events of a person's stepping and walking process in three dimensions.

Experimental studies on transient lubrication have also taken the attention of the researchers. Ren et al. [11] built and introduced a device for the experimental investigation of the problem of contact between two bodies. This device creates a sinusoidal variable force and is capable of measuring the thickness of the lubricant layer. The thickness and shape of the lubricant layer are measured using the optical interference method and high-speed photography techniques. Also, the dynamic component of the load is determined by a power converter with a fast frequency response, and the instantaneous rolling speed is also measured. To reveal the characteristics of elasto-hydrodynamic (EHD) lubrication (EHL) under heavy loading and variable speed conditions, Miao [12] conducted relevant experiments with a self-developed optical interference EHL experimental device. Trivedi, and Bhatt [13] evaluate the friction and wear behavior of cylinder liner and piston ring materials for four-stroke engine systems. The friction and wear experiments are performed using a pin-on-disc tribo tester to investigate the effect of lubricants and load conditions. Zhang, and Glovnea [14] measured the film thickness measurements of grease-lubricated EHD contacts subjected to harmonic load variation. The experiments are carried out in a test rig under both steady-state and variable loading conditions. Most of the wear test devices are based on constant load and limited research has been done with variable load, one of the reasons for which is the unavailability of suitable laboratory devices.

The present study has two main sections, the first one is the completion of the existing laboratory device to have the ability to produce variable load and the second step is to conduct relevant tests to check the possibility of performing different tests with different load patterns. The friction force is the comparison parameter in tests. After this study, the pin-on-disc wear test located in the mechanical properties laboratory of the engineering department of Shahrekord University is equipped with a load change system. The working basis of the variable applied load system is based on an electromagnet coil which is controlled with an electronic control unit. By changing the input voltage of the coil, the intensity of the magnetic field changes, and as a result, the magnetic force changes. By placing this magnet instead of the fixed load lever of the device, the amount of applied load can change and different load patterns can be created during the lubrication process.

2. Load-varying system design

2.1. Pin on disc wear test device

The pin-on-disk tribo-test is one of the devices used to predict the tribological behaviour of engineering materials and alloys in operational conditions and to study the EHD contact conditions. By measuring the friction coefficient during the test, this device delivers a criterion for comparing the results, and also a tool for validation of numerical analyses. Therefore, most of the numerical analysis is designed based on the geometry of this device, which is the contact of a pin and a disc, as shown in Fig. 1.

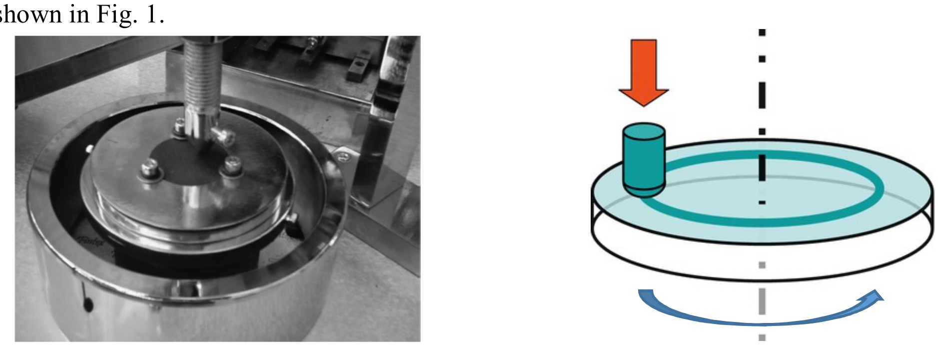

Fig 1. Schematic (right) and realistic (left) of pin-on-disk device

2.2. Development of the load change mechanism

The design idea of the system is based on a variable electromagnetic force produced by an adjustable magnetic field of a winding coil. The magnetic coil consists of two parts including the U part which connects to the ground, and the I part which connects to the device's load lever. The U part of the magnetic coil is made of an iron sheet that has a ferrite coating with a thickness of 0.5 mm. The sheet has the standard length of 150 mm and the width of 25 mm. The selection of the transformer core, the size of the sheets, the core's thickness, the coil's number of turns, and the wire's thickness are presented to Table 1. The I part is formed by putting 90 sheets next to each other with the total thickness of 45 mm.

When the current passes through the coil, the U part of the transformer magnetizes. By changing the coil's input voltage, the magnetic field's intensity around the coil changes, and as a result, the magnet's attraction force changes. According to Fig. 2, The force created between these two parts after applying electric current is calculated as follows:

$$F = \frac{2}{5}\frac{\mu_0 N^2 I^2 xyr^2}{g^2} \tag{1}$$

where I is the current intensity and g is the distance between U and I.

$$r = \frac{(2y + 2\pi x)N^2}{\sigma \cdot A} \tag{2}$$

$$A = xy$$

Table 1. The minimum number of winding turns and core width is according to the standard length of the UI transformer core sheet.

The standard length of the core sheet	The standard width of the core sheet	The minimum number of coil turns	Current through the coil	Core width	Core cross-section	NI	v
150	25	400	2	25	1250	0.64	1.864
120	20	400	2	31.25	1250	0.64	1.606
105	17.5	400	2	35.714	1250	0.64	1.491
96	16	400	2	39.062	1250	0.64	1.429
84	14	400	2	44.643	1250	0.64	1.357
78	13	400	2	48.077	1250	0.64	1.328
66	11	400	2	56.818	1250	0.64	1.289

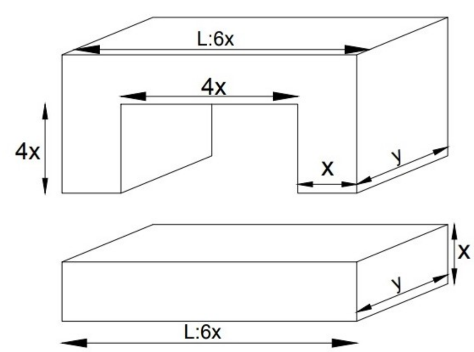

Fig 2. Schematic of the UI core of the magnetic coil

Other parameters according to the designed coil are as follows:

$$\sigma = 50 \times 10^{6}\, m^{-1}\ ,\ x=25 \times 10^{-3}\, m,\ y=45 \times 10^{-3}\, m \\ L=150 \times 10^{-3}\, m,\ N=500 \tag{3}$$

The shorter the distance between the U and I parts, the greater the attraction force, and vice versa. Therefore, factors affecting the amount of force applied on the pin-on-disc device are:

1- Coil input voltage
2- Coil input current
3- The distance between the U and I parts

The magnet winding of the coil uses a 1.1 mm-diameter wire which turns around the iron core near 500. To prevent the sheets from separating, they are connected by argon welding. Owing to the magnetic effect on the other part of the device, the chassis material is selected from aluminum. Figure 3 shows the U and I parts and how they are assembled.

The I part is connected to the horizontal arm of the device where the weight is previously connected by a long screw. Balance weights are added to the other end of the arm to balance the additional weight. There is a mechanism consisting of screws and springs on the I part to adjust and change the distance difference between the two plates U and I, which is shown in Fig. 3.

2.3. Load change control unit

To create different load patterns in different time intervals, the input electricity to the circuit should be changed. The intensity of the current passing through the coil is dependent on the supply voltage, and the force produced in the coil is related to the intensity of the passing current as a power of two. Therefore, the force applied to the system is controlled and different force patterns can be formed by changing this current intensity in a certain period.

The electric circuit has five relays, which are activated in specific and adjustable time intervals and allow the current to pass. At first, the first key or relay is active and the rest of the relays are inactive, after a certain period, the first key becomes off from the circuit and the second relay is activated immediately, and the rest of the relays are activated in the same way. The current that is passed through each relay is controlled by a microcontroller. This cycle repeats itself endlessly. Figure 4 shows the overview of the controller circuit designed and programmed for the present study.

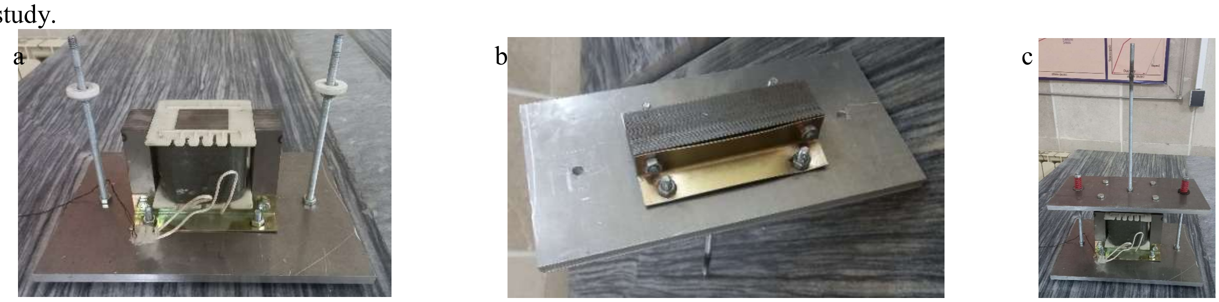

Fig. 3. (a) U part; (b) I part; (c) Magnetic coil assembly

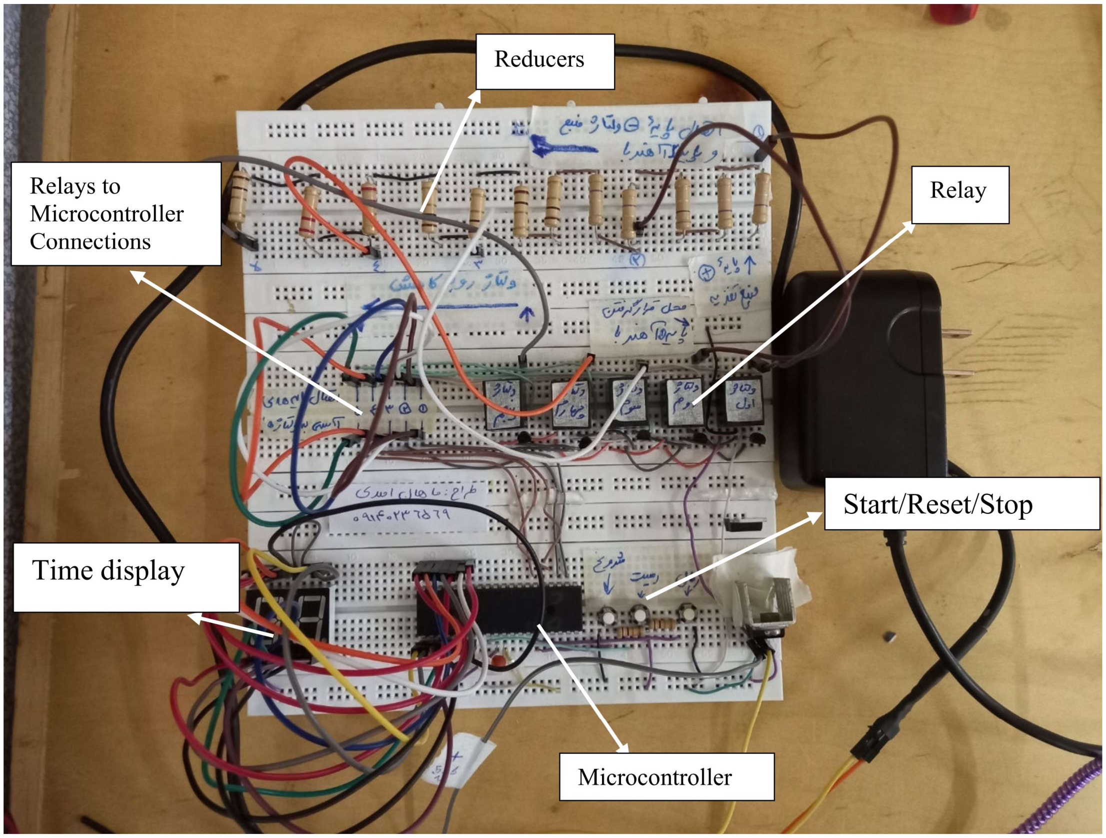

Fig. 4. The control unit

3. Test setup

Modeling of EHD contact is usually validated with the pin-on-disc device. After equipping the device with a variable load system, attempts are made to investigate the behavior friction force measured by the device for various load patterns of the system. In this study, the experimental measurement of an EHD contact lubrication under the effect of variable load in ascending, descending, sinusoidal, and ascending-descending patterns is made at two different linear speeds: U_1=0.28 m/s and U_2=0.094 m/s. The time steps of relays for changing the force are chosen equal to 4 seconds which means that by considering the five relays, a cycle lasts 20 seconds. The 10W-40 automotive oil with a viscosity of 0.013 Pa.s has been used as a lubricant. The material of the test samples is st37 steel and the pin material is 100-chrome-6 bearing steel with a hardness of 64 Rockwell and a roughness surface of 0.05 micrometer.

Table 2. Fluid, pin, and sample characteristics in contact experimental analysis

Parameter	value
Pin radius	2.5 mm
Pin width	2 mm
Pin material	100 Cr 6 Steel
Sample material	St37 Steel
Relative velocity of surfaces	0.28 m/s and 0.094 m/s

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The test samples are made by punching a sheet with a thickness of 2 to 5 mm. In the next step, a 6.2-mm hole in diameter is made in the center of the flakes, and after that, the surface of the samples is polished to minimize the roughness by grinding with a magnetic stone. Figure 5 shows the prepared sample of the test.

In this study, each force cycle is repeated 20 times and the related data is recorded. Thereafter, in order to eliminate any probable noise, the average of recorded data is used. The data recorded in the pin-on-disk device software includes time, friction force, and travel length. The pin-on-disc device records the friction force every 0.001 seconds. Table 3 shows the normal load value for different patterns at each time step.

4. Results

The effect of ascending variable load on EHD contact for two speeds of U_1 and U_2 is experimentally evaluated and the results of friction force and normal load are summarized in Fig. 6. By comparing the changes of measured normal load in Fig. 6(a) with the changes of friction force in Fig. 6(b), it is clear that the friction force completely follows the pattern of vertical force changes. An increase in speed causes the formation of a thicker layer of fluid, which can lead to a reduction in friction due to a lower probability of surface roughness interaction.

When the normal load in the interface contact between the two objects changes, for example, it increases, the two objects approach each other and compress the between lubricant layer. The compression of the lubricant layer creates a pressure in the fluid that prevents the two bodies from touching each other. This phenomenon is so-called the squeeze film lubrication. The squeeze film lubrication is stronger at higher speeds as shown in Fig. 6(b).

a b

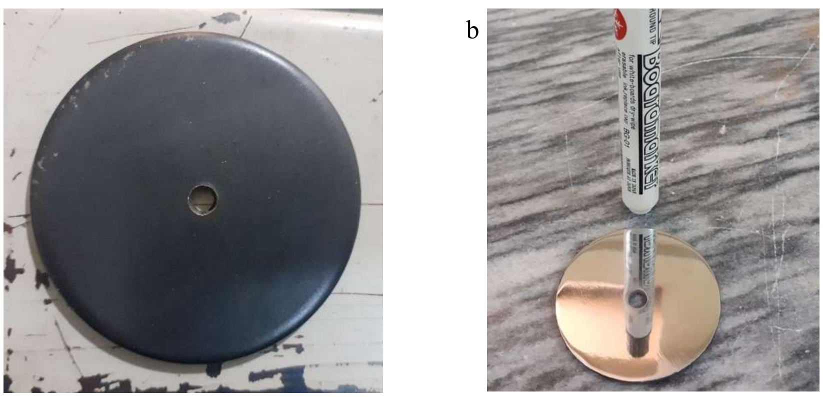

Fig. 5. (a) Test sample before polishing; (b) Test sample after polishing

Table 3. The Normal load (×10 N) on the pin at two speeds U1=0.28 and U2=0.094 m/s

	First step	Second step	Third step	Fourth step	Fifth step
Ascending	0.15	0.2	0.24	0.335	0.425
Descending	0.425	0.335	0.24	0.2	0.15
Fluctuating	0	0.425	0.15	0.335	0.2
Ascending-Descending	0.15	0.24	0.425	0.425	0.24

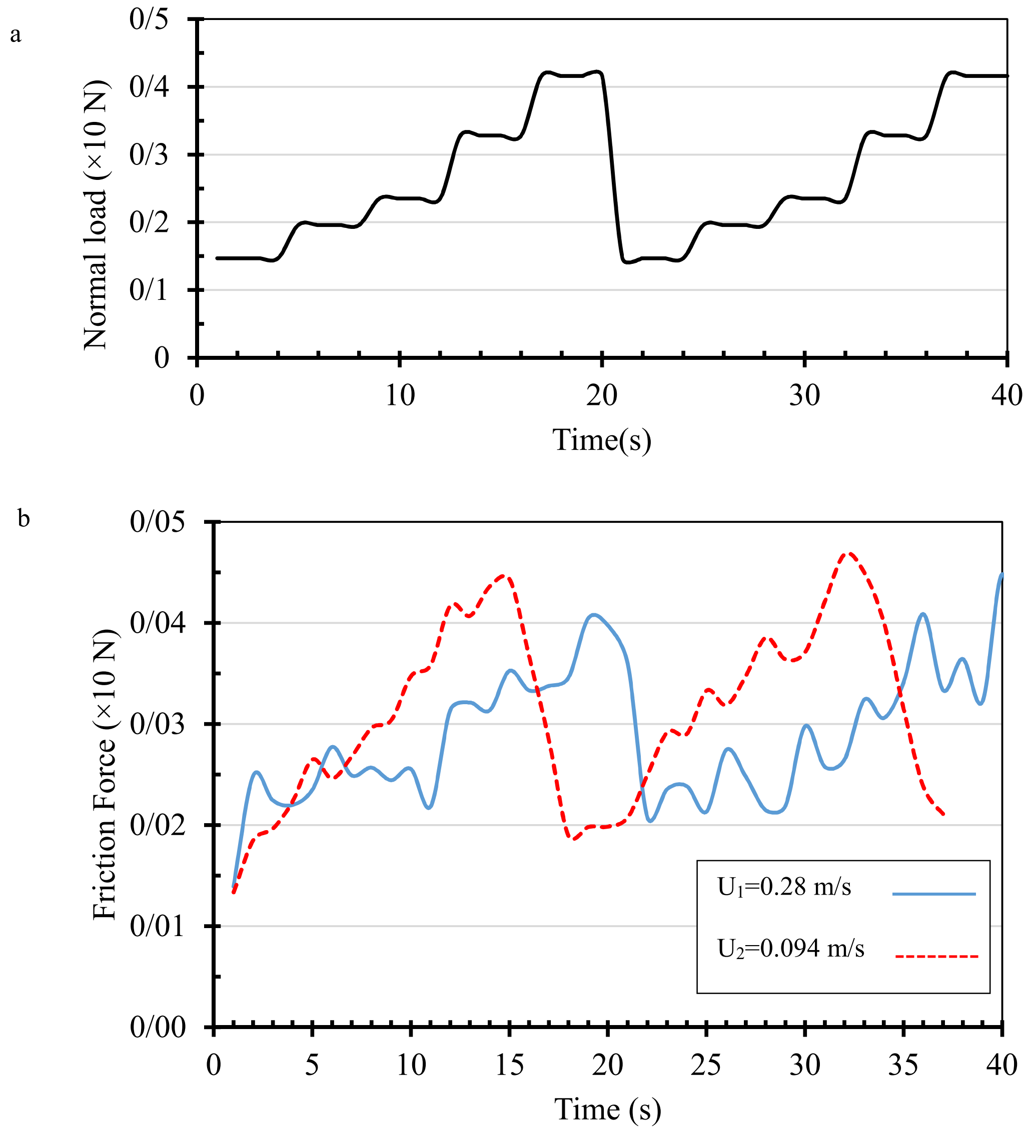

Fig 6. (a) Normal load for ascending pattern; (b) Friction force changes due to speed change U_1=0.28m/s and U_2=0.094m/s

It can be seen that the general behavior of the coefficient of friction is opposite to the pattern of force. This is justified because the changes in normal load are larger than the changes in friction force. Thus, in high normal forces, the friction coefficient is smaller. At the end of the time step and following an increase in the force, the friction coefficient decreases with a rapid slope, which can be due to the fact that the fluid does not have the opportunity to move between the two surfaces in a limited time.

In Fig. 7, the results of descending normal load are shown. By changing the force after each 4 seconds, the friction acts according to the behavior of the vertical force. With the reduction of vertical force, the coefficient of friction increases due to the difference in the size of the vertical force changes as compared to the changes in the friction force. In this pattern, the surface relative speed does not affect the friction, and the measured data are almost close to each other. This is due to the nature of the load reduction which helps the lubricant fill the contact area. The phenomenon of squeeze film lubrication does not have any effect on decreasing the normal loads; therefore, the observed behavior in the decreasing force pattern is completely consistent with the vertical force of the friction force.

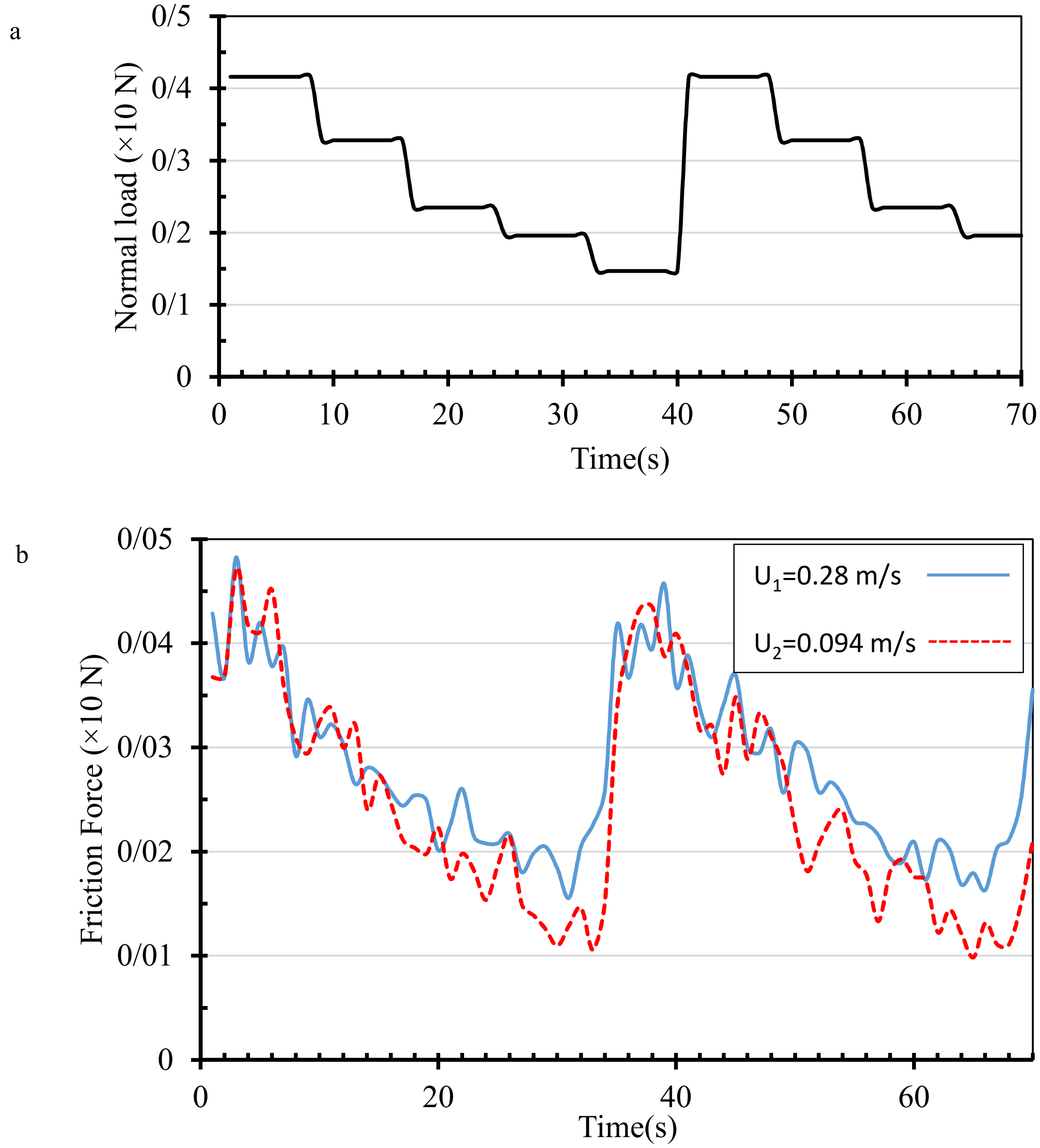

Fig 7. (a) Normal load for ascending pattern; (b)Friction force changes due to speed change U_1=0.28m/s and U_2=0.094m/s

The third pattern that experimentally investigated is a fluctuating variation of normal load on the pin and disc contact at U_1 and U_2 speeds. In this stage, the effect of the force changes in the form of a fluctuation wave, starting from zero, and, in each cycle, the vertical force increases maximally in the first step, decreases maximally in the second step, and again increases but not to the extent of the first step, decreases but not up to the level of the second step in the fourth step. Finally, in the last step, it returns to zero and completes the cycle. The results of this fluctuating load are shown in Fig. 8. The squeeze film lubrication phenomenon is observed when the vertical load increases suddenly. A kind of resistance to the growth of friction force is seen due to an increase in the load. This phenomenon is clearly clear in the 20 to 30-seconds interval. As shown in Fig. 8, It can be easily seen that the friction force at both speeds follows the wave pattern of the vertical force. The friction coefficient behaves differently against the wave change of the normal force so that it increases initially and acts against the pattern of force changes in the subsequent fluctuations. The initial behavior seems to occur due to the presence of zero force in the normal load cycle. At the beginning of the cycle, the friction coefficient increases with a sudden increase in force, and then it behaves according to the descending and ascending forces.

To experimentally investigate the effect of variable ascending-descending load on EHD contact at different speeds, another test is accompanied. In this test, the normal force increases initially and then decreases. Figure 9 shows the results of this test.

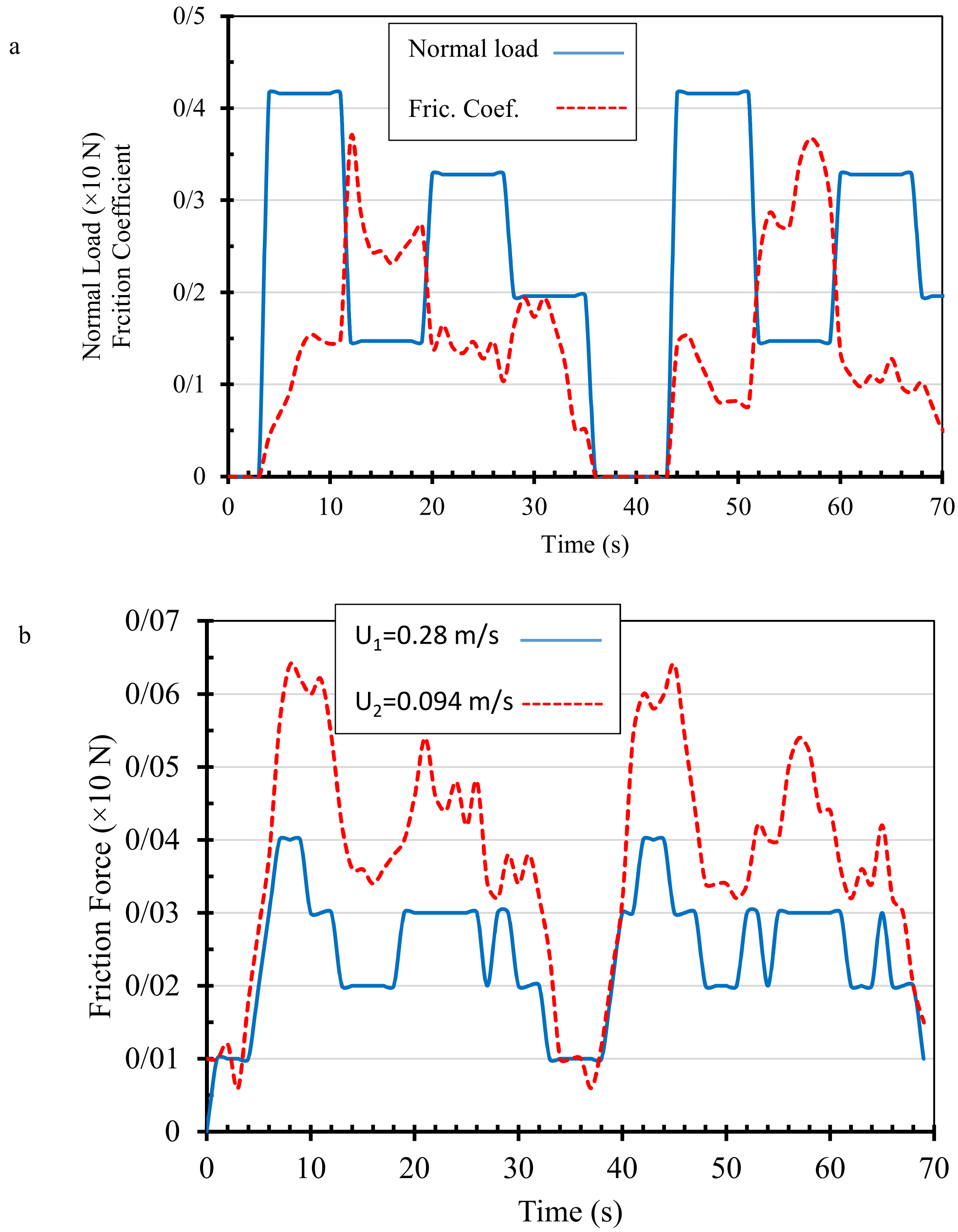

Fig 8. (a) Normal load for the fluctuating pattern; (b)Friction force changes due to speed change U_1=0.28m/s and U_2=0.094m/s

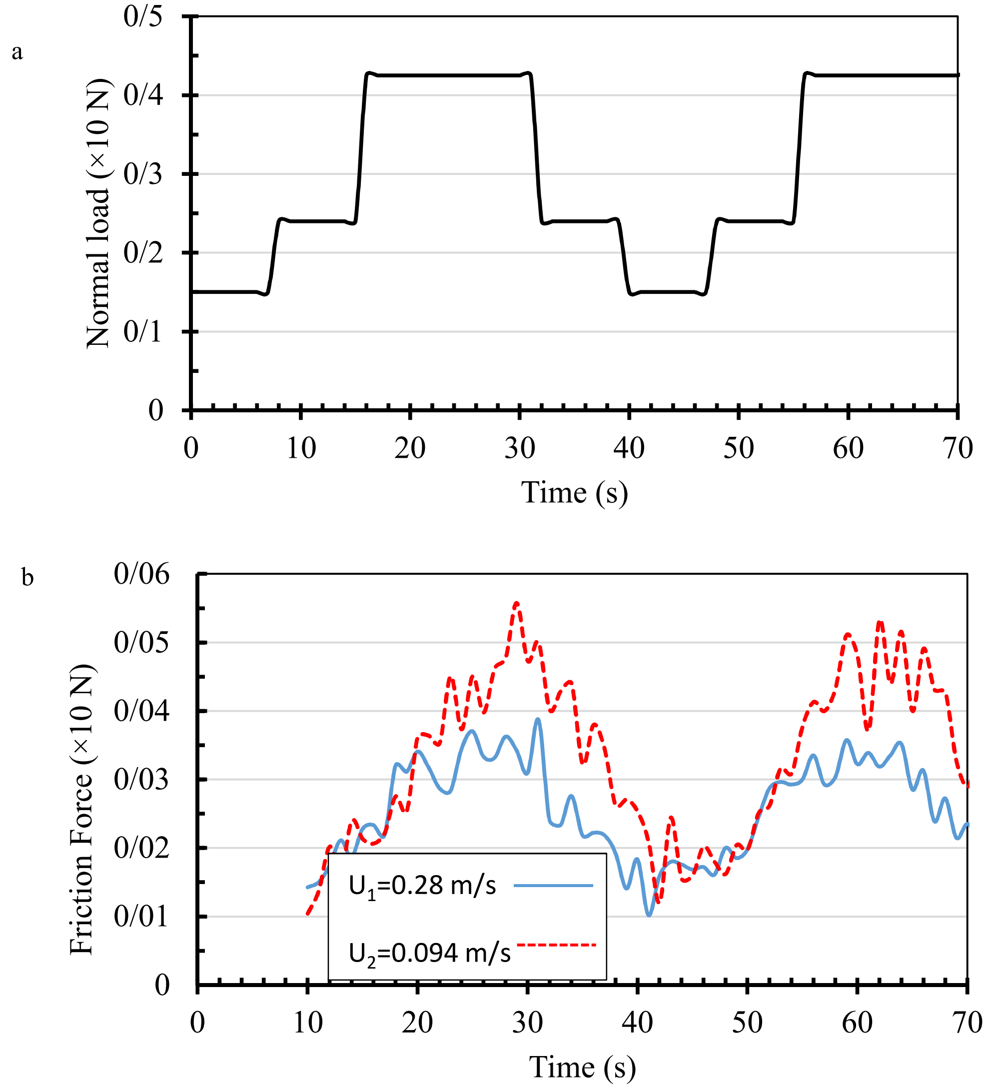

Fig 9. (a) Normal load for ascending pattern; (b)Friction force changes due to speed change U_1=0.28m/s and U_2=0.094m/s

In this test, the behavior of variations in the friction can be considered as a combination of the states of ascending and descending force change. As expected, in the whole cycle, the friction coefficient changes in contrary to the applied force. The higher speed causes a thicker lubricant film between the surface and as a result, lower friction is obtained in the measurements.

5. Conclusion

By equipping the load change system with the pin-on-disc test device, four variable load patterns on elastohydrodynamic lubrication contact are investigated. To minimize the effect of surface roughness, small normal forces are used and the test samples are polished as much as possible. The results of this research are as follows:

1- The effect of speed on friction force: the relative speed of the surface is one of the important parameters of lubrication which can affect the friction force. According to the measurement results and as expected in the theory, when the entraining velocity increases, the friction force decreases. In the experimental studies, it is seen that the variation of friction force in all cases decreases with an increase in the linear speed. This is due to the important role of the surface roughness on the friction force. In real conditions, by increasing the linear speed, and with a greater thickness of the lubricant film form, the probability of roughness interaction of the two surfaces is reduced, decreasing the friction force.

2- Friction force changes following the force change pattern: In the present study, it is shown that the friction force follows the vertical force change pattern in all the conditions. This issue shows the importance of considering the transient condition of the normal load in the analysis of elasto-hydrodynamic contact.

3- The friction coefficient may change reverse to the vertical force pattern: The normal load changes are in the order of one newton in each time step, while the friction force changes were in the order of a tenth of one newton. Therefore, the friction coefficient shows the opposite behavior to the pattern of normal load in a complete cycle. During a step when the vertical force is constant, the friction coefficient increases due to the removal of the squeezing effect of load change. In case of ascending change of the normal load, in each step when the force changes, the friction coefficient does not change proportional to the force and decreases as the fluid cannot escape from the contact area. In case of a descending change of the vertical force, in each step, the force decreases and causes a thicker lubricating film to be formed. In this pattern, the effect of fluid layer shearing causes a significant increase in the friction coefficient.

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