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Effects of Velocity and Load on Chattering Occurrence in Grease-Lubricated Sliding Electrical Contacts

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Sliding electrical contacts are used to detect the motion of mechanical components. Grease is often used to reduce the friction and wear of sliding electrical contacts. Chattering sometimes occurs at low temperatures in grease-lubricated sliding electrical contacts. However, the causes of chattering are not well understood. We developed a test apparatus to simulate sliding electrical contacts. Using this apparatus, we studied the effects of sliding velocity, contact load, ambient temperature, and oil and grease viscosity on chattering occurrence. The results showed that chattering occurred at high sliding speeds, low contact loads, and with high-viscosity greases. By measuring the displacement of the upper contact, we also showed that the shape of the lower contact influenced the chattering characteristics. The causes of chattering are concluded to be an increase in the thickness of the oil layer between the upper and lower contacts due to hydrodynamic effects and an increase in the resistance of the oils or greases.

1. INTRODUCTION

Mechanical operations in consumer electronics, vehicles, and robots and the like are controlled by electrical signals. Frequently, the switching of the operational modes in the above applications is realized by mechanical contact/noncontact switching of metal points of contact. A neutral starter switch used in sending vehicle gear change signals to a vehicle computer is one such switch. Switches of this type are sliding electrical contacts in which problems related to friction and wear are encountered. Grease for electrical contact is used in sliding electrical contacts to prevent any

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deterioration of their properties by wear. Properties required from electrical contact greases are (1) the electrical insulation and (2) the electric conductivity at the state when a contact is closed [1]. We found that when grease is used, the mechanism of electric conductivity of an electrical contact is determined by a thin-film contact electric conduction whereby electric current flows through surface profile projects coming through a thin film when a grease-lubricating film in an electrical contact becomes very thin (below some nanometers), although the grease is electrically insulating [2].

There is a wide range of applications of electrical contacts, and it is necessary that the contacts would maintain their stable electric conductivity from high-temperature to low-temperature conditions. However, electric conductivity is particularly unstable under low-temperature conditions, and an interruption of the electric current flow (which is called chattering) occurs even at the closed state of a contact [3]. When chattering takes place, it becomes possible that an operation intended by changing the state of the electrical circuit would not be accomplished. Therefore, resistance to chattering is required in greases used in sliding electrical contacts.

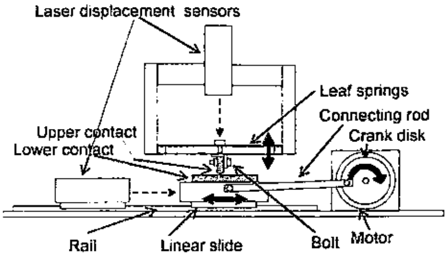
Until now, chattering due to bouncing in electrical contacts, such as lead switches, has been considered by Miedzinski et al. [4], but in that case, relaxation oscillations with one degree of freedom have been considered, and reports on the chattering of sliding electrical contact cannot be found. Ikuma et al. [5] have reported that chattering properties under low-temperature conditions strongly depend on the dynamic viscosity of base oil used in the grease. However, the effect exerted by loads applied to electrical contacts and that of the speed of sliding of the electrical contact have not been clarified.

Therefore, the authors have developed a sliding electrical contact testing apparatus driven by a crank mechanism and capable of successively varying the speed of sliding of a lower contact element [6]. Preliminary experiments performed using this testing apparatus allowed us to measure the contact voltage during contact sliding and comparing the occurrences of chattering at normal and low temperatures, respectively. We found that the chattering occurs more intensively under lower loads and higher sliding speeds at low temperature. In this work, chattering generation conditions are specified by measuring the temporal frequency and the duration of the chattering under different conditions established by using different load, different speeds of sliding, different environmental temperature, and different base oil/grease to clarify the source of the chattering generation. The results are summarized in this work.

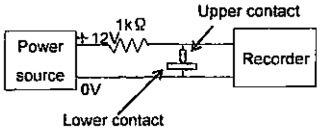
2. OUTLINE OF THE EXPERIMENTS

We structured an experimental apparatus so that it would allow left and right movements of a lower contact connecting with an upper contact to simulate a sliding electrical contact. The upper and lower contacts were coated by grease, a load was applied to the electrical contact by a spring, and a direct current voltage of 12 V was applied to the electrical contact. The sliding experiments were performed under the above conditions by 2 s measurements of a change of electrical contact voltage, a vertical displacement of the upper contact, and right-hand and left-hand side displacements of the lower contact. Moreover, sideways displacements are used to calculate the speed of sliding.

In this work, the sliding experiments were performed at normal temperature (20°C) and low temperature (−20°C) by using three types of base oil viscosity greases prepared by using 12 lithium hydroxystearate (Li-12OHSt) as a thickener and four types of base oil differing by kinematic viscosity. The effects on a vertical displacement and load of the upper contact, temperature and the speed of sliding were determined from results obtained in experiments on base oils and greases showing the generation of the chattering.



(a) Experimental apparatus

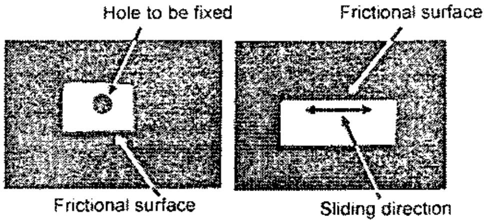


(b) Electric circuit

Fig. 1
Schematic diagram of the experimental apparatus and electrical circuit.

2.1 Sliding Testing Apparatus

A schematic diagram of the sliding testing experimental apparatus is shown in Fig. 1(a). In the figure, solid arrows show the direction of movement and dotted arrows indicate the direction of irradiation by a laser displacement meter. The shaded area in the figure indicates electrical contact. The lower contact element is located over the sliding plane horizontally to the drawing plane, and the upper contact element is located over that so that it would be orthogonal to the sliding plane. The upper contact element and the lower contact element are shown in Fig. 2. The upper contact element is 2 mm thick and 13 mm wide and is made of a sheet of copper 8 mm thick and is provided with a hole of ϕ4 in the central part. The lower contact element 2 mm thick and 29 mm wide is made of a sheet of copper 10 mm thick. The respective sliding surfaces were machined to a cylindrical shape with radius $R1$ and surface roughness R_a = 0.5 μm, and their surface was silver plated, forming a coating 10 μm thick. In the process of cylindrical machining of the lower contact element, larger amounts of material are removed from the central parts on both ends (see Fig. 2). When looked at



(a) Upper contact (b) Lower contact

Fig. 2
Picture of silver-plated sliding electrical contact.

from the front of the figure, a protrusion with the radius of curvature of about 2.5 m can be observed on the sliding surface, discussed Section 3.5.

The circular arc parts of the respective sliding surfaces come into contact orthogonally; therefore, the contact between them is a point contact. Supposing that at a load of 1.0 N the contact between a sphere with the radius of 1 mm and the flat surface of silver material occurs in either case [7]. The radius of the contact area can be determined as about 25 μm, according to the Hertzian theory of elastic contact. Because the magnitude is sufficiently smaller than the amplitude 14.7 mm of alternative movements, established contact can be considered as a point contact. The upper contact element consists of a ball and an electrode attached to a parallel leaf spring (see Fig. 1(a)). As shown in the upper part of the figure laser displacement meter, the upper contact and the parallel leaf spring are able to be displaced in the vertical direction simultaneously. The parallel leaf spring can apply a static load to the electrical contact. Once a load is applied, vertical displacements of the upper contact element start to be measured by a laser displacement meter. A load applied by the parallel leaf spring and a vertical displacement are linearly correlated. The resolving power of the laser displacement meter is 200 nm. The spring constant of the parallel leaf spring is about 0.55 N/mm; therefore, at an applied load of 0.2 N, vertical displacement is about 0.36 mm, and at an applied load of 1.0 N, displacement reaches about 1.82 mm. Because the upper contact element is copper, it shows a very low level of deformations, and bending though a tendency of microscopic vertical displacements of the upper contact element is observed during its sliding, which is explained by the action of a constant load in a constant direction. The lower contact element consists of an insertion and an electrode inside the acrylic base and the base is fixed to a slider movable over rails. The slider is inserted between the rails lying on both sides of the rails. An aluminum crank disk is attached to the output shaft of a motor shown in the right-hand side of the figure and is rotated by the motor, the alternating movement is controlled by a crank mechanism, and the slider performs simple harmonic oscillations. A rod connecting the crank disk and the slider connects the base with the fixed slider and the crank disk by a screw. The rod connecting the crank disk and the slider is arranged in parallel to the direction of the slider movement. The laser displacement meter is placed on the rails used by the slider to measure displacements in the horizontal direction. Displacement of the lower contact element is calculated by measuring the horizontal position of the slider by the laser displacement meter. Therefore, we suggest that the sliding direction has no scatter. The resolving power of the laser displacement meter is 3 μm. This structure allows us to change sinusoidally the horizontal position of the lower contact element and its speed of sliding by changing the angle of the motor rotation.

Figure 1(b) is a schematic diagram of an electric circuit used to measure a voltage on the electrical contact. A resistance element of 1 kΩ is used to prevent any short circuits. When DC voltage of 12 V is applied to both contact elements sliding under loading conditions, electric current does not flow if the contacts are separated and the voltage will be 12 V, but when the electric current flows, the voltage will be 0 V. Temporal variations of a contact voltage and those of an output voltage of the laser displacement meter are registered by a recorder.

2.2 Experimental Conditions

Conditions used in this experiments performed by applying DC voltage of 12 V to the electrical contact are shown in Table 1. The experiments were performed as normal-temperature experiments at 20–22°C and as low-temperature experiments by maintaining temperature constantly at −20°C. The applied load was 1.0 N, which is of the same order as that used in the normal operation of the sliding electrical contact, or 0.2 N, which was lower than a normal load. The maximal sliding speed of the lower contact element performing simple harmonic oscillations with the double amplitude of 14.7 mm was 47 mm/s at a frequency of about 0.9 Hz and 94 mm/s at a frequency of about 1.9 Hz. The voltage measurement time was 2 s, and sampling frequency was 62.5 μm.

Table 1
Test conditions.

Applied voltage , V	12
Temperature , °C	20~22 , −20
Load , N	0.2 , 1.0
Sliding amplitude , mm	14.7
Maximum sliding velocity , mm/s	47 , 94
Test duration , s	2

Table 2
Base oils used in tests.

	Oil1	Oil2	Oil3	Oil4
Oil type	Poly-α-olefin			
Kinematic viscosity , mm^2/s	18	47	420	37500

Table 3
Greases used in tests.

	Grease1	Grease2	Grease3
Base oil	Poly-α-olefin		
Thickener	Lithium 12-hydroxystearate		
Kinematic viscosity , mm^2/s	18	47	420
Worked penetration	About 280		

Base oils used in this experiment are shown in Table 2. Poly-α-olefin (PAO) [3], which is synthetic hydrocarbon with a low pour point, is used as the base oil. The experiments were performed using four kinds of oils, oil 1–oil 4, with kinematic viscosity at 18–37,500 mm^2/s at 40°C. At a low temperature of −20°C, oil 1–oil 3 were used supposing that at low temperature, the kinematic viscosity of base oils would be 50 to 1000 times higher [8] than that at 20°C and oil 4 whose kinematic viscosity is 37,500 mm^2/s at 40°C was used.

Greases used in the experiments are shown in Table 3. Three types of greases were used: grease 1–grease 3, of the same consistency prepared by adding Li-12OHSt as a thickener to base oils 1–3 with no other additives used.

Base oils and greases were applied to the entire lower contact element so that they formed coatings about 0.5 mm thick. After a coating was applied, the electrical contact was set to perform four to five cycles of sliding under load conditions, thereby removing any deviations in base oil and grease coatings.

Four cycles of testing were performed under the same experimental conditions. A temperature change on sliding components was very low even when they slid repeatedly during the experiment. Measurements of the voltage above 1 V in the electrical contact were performed in the intervals when the electric current flow did not occur. The time of a chattering generation occurrence under conditions determined by averaging results obtained in four experimental cycles was taken to be *t* and calculated by estimating a stroke of alternating movement during a period when an electric current flow did not occur. The frequency of temporal chattering generation and its duration were estimated by comparing the parameter *t* under different conditions.

3. EXPERIMENTAL RESULTS AND DISCUSSION

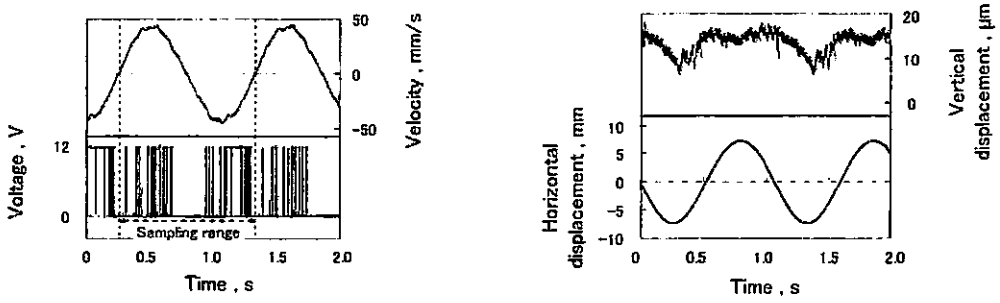
3.1 Explanation of Typical Occurrences of Chattering

A voltage of typical electrical contact and speed of sliding during the chattering generation are shown in Fig. 3(a). Respective horizontal displacements of the lower contact element and respective vertical displacements of the upper contact element are shown in Fig. 3(b). A bias at any time moment during the horizontal displacement of the lower contact element was taken to be the sliding speed. A vertical displacement was considered to be positive when the upper contact element separated from the lower contact element. A horizontal displacement was taken to be 0 mm in the central position of the amplitude of alternating movements. As it is evident from Fig. 3(a), the sliding of the lower contact element in the horizontal direction was controlled by the crank mechanism; therefore, the speed of sliding was maximal or minimal at a horizontal displacement of 0 mm. The generation of chattering starts in the process of increasing the sliding speed from 0 mm/s (or in the process of decreasing of the sling speed from 0 mm/s). Chattering terminated in the process of reducing the sliding speed to 0 mm/s (or in the process of raising the sliding speed to 0 mm/s). Correlation between chattering and sliding speed is not observed. Observations of the speed of sliding in Fig. 3(a) and a horizontal displacement in Fig. 3(b) show that the sliding movements are realized by a pattern close to the sinusoidal one. When observing vertical displacements shown in Fig. 3 (b), it becomes clear that a difference in displacement during a cycle of alternating movement amounts to about 10 μm.

Below we determine the effects exerted by the kinematic viscosity of base oils and greases and the effects by applied loads and the sliding speed. Finally, we consider the thickness of lubricant films forming in the electrical contact.

3.2 Effect of Kinematic Viscosity of Base Oils

The chatter generation time *t* when using base oils and greases is shown in Figs. 4 and 5, respectively. In experiments performed at normal temperature, chattering occurs when using oil 4



(a) Sliding velocity (right axis) and contact voltage (left axis)

(b) Vertical (right axis) and horizontal (left axis) displacement

Fig. 3
Typical results of chattering occurrence and data definition.

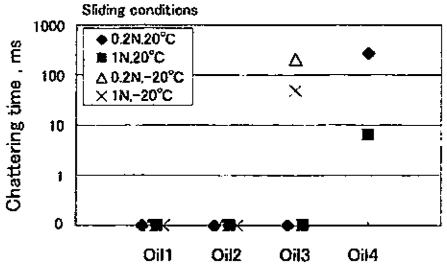


Fig. 4
Effects of base oils on chattering time in 1 cycle.

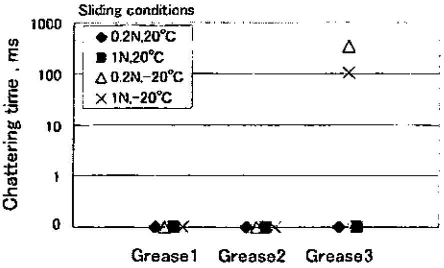


Fig. 5
Effects of greases on chattering time in 1 cycle.

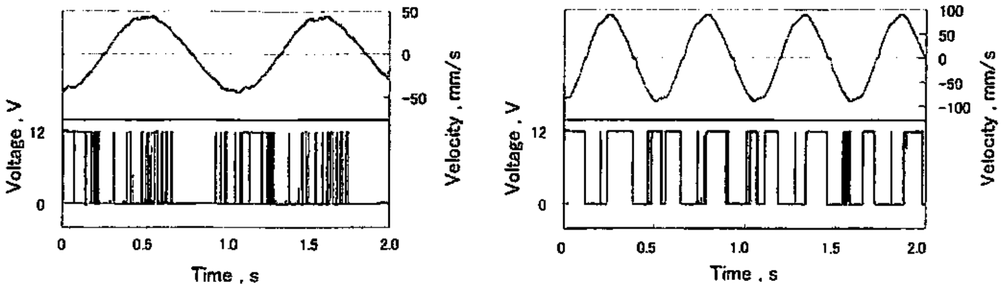
only regardless of applied loads. In the low-temperature experiments, the occurrence of the chattering was observed when oil 3 and grease 3 were used. At –20°C, the kinematic viscosity of base oil of oil 3 is about 40,000 mm^2/s. Results obtained in the low-temperature experiments using oil 3 and grease 3 containing the base oil of the same kinematic viscosity (Figs. 4 and 5) show that their chattering generation times are of the same order, and results obtained by low-temperature experiments using oil 3 and results obtained in normal temperature experiments using oil 4 (Fig. 4) where the base oil kinematic viscosity is of the same order in both cases show a chattering generation time of the same order. Therefore, we can conclude that one reason behind the chattering generation when using grease at low temperature is an increase of the base oil viscosity. The conclusion conforms to the results published by Ikuma et al. [5].

3.3 Effect of Applied Load

Observing the effect exerted by applied load in Figs. 4 and 5 shows that the time of chattering is shorter at applied load 1 N than at load 0.2 N under all chatter generation conditions. The phenomenon is explained by the fact that when a load applied is lower, the separation between contact elements increases, and because the probability of the presence of grease between the contact elements increases, the time of chattering generation grows longer.

3.4 Effect of Sliding Speed

Results obtained at a maximum sliding speed of 47 mm/s and those obtained at sliding speed 94 mm/s established by a twofold increase of motor rotational speed are shown in Fig. 6(a) and Fig. 6(b), respectively. In the experiments performed using oil 4 at 20°C (Fig. 4) and using oil 3 (Fig. 4) and grease 3 (Fig. 5) at –20°C, the respective chattering times are of the same order under applied load 0.2 N; therefore, the experiments using oil 4 were performed at 20°C and applied load 0.2 N. The waveform of the sliding speed in Fig. 6(b) seems to deviate from the sine wave. A bearing with a same-side inside diameter as the outside diameter of a screw in a through hole provided in a connecting rod was fitted in the part connecting it with a crank disk, reducing the play of the joint. However, with an increase in motor rotational speed, a load acting on the through hole grew larger and the influence of the play of the joint became stronger, resulted in a deviation of the waveform of the sliding speed from the sinusoidal waveform. However, chattering affects the sliding speed, but no correlation with an acceleration determined from the sliding speed bias was found. Therefore, we suggest that the effect of a deviation of the waveform of the sliding speed from the sinusoidal form



(a) Sliding velocity (right axis) and contact voltage (left axis) , (±47mm/s)

(b) Sliding velocity (right axis) and contact voltage (left axis) , (±94mm/s)

Fig. 6

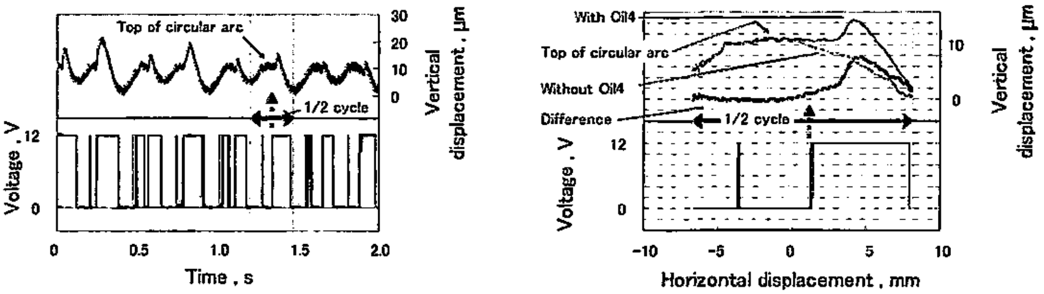
Comparison between the chatterings in maximum sliding velocity 47 mm/s and 94mm/s (load 0.2 N, with Oil 4).

on results obtained in this work is rather weak. As it is evident from Fig. 6(a) and Fig. 6(b), chattering starts generating when the sliding speed increases from 0 mm/s (or decreases from 0 mm/s) and terminates when the sliding speed decreases to 0 mm/s (or increases to 0 mm/s). Because generating chattering takes longer when the electric current flow does not occur in Fig. 6(b) than in Fig. 6(a), we conclude that chattering generation starts more easily at higher sliding speeds.

The Hamrock-Dowson equation (9) shows that the thickness of oil films formed between the contact elements moving at the point contact state is inversely proportional to an applied load and is proportional to the oil viscosity and the sliding speed. When there is an increase in oil film thickness, it becomes hard to provide electric conductivity because of the insulating properties of base oil and grease.

3.5 Increasing Oil Film Thickness

Results considered in Sections 3.2 and 3.4 show that an occurrence of chattering leads to an increase of the oil film thickness and that is verified by performing measurements of vertical displacements of the upper contact element at a maximum sliding speed of 94 mm/s. Voltage and vertical displacement of the upper contact element under conditions similar to those shown in Fig. 6(b) are shown in Fig. 7(a). Voltage and vertical displacement of the upper contact element during alternating movements of the lower contact element with amplitude 14.7 mm, the sliding covering half the cycle of simple harmonic oscillation (the range of a half cycle is indicated by the double arrow in Fig. 7a)) are shown in Fig. 7(b). In Fig. 7(b), vertical displacements when oil 4 (the line indicating "With oil 4") is used and vertical displacements when a base oil is not used (the line indicating "Without oil 4") show a difference (the line indicating "Difference"). Observations of vertical displacements when base oil is not used in Fig. 7(b) show a slight lift up of about 5 μm from the left-hand side starting point to the horizontal position of about −2 mm and a downward shift of about 10 μm at the end point. We can conclude from the above that the sliding surface of the lower contact element protrudes with the radius of curvature of about 2.5 m as was established in Section 2.1. The surface profile of the sliding surface of the lower contact element was measured along a distance of 20 mm in the direction of sliding using a surface profile measuring apparatus with a resolving power of 10 nm verifying the existence of a protrusion with a radius of curvature of 2.5 m. On the other hand, observing vertical displacements when using oil 4 show an elevation compared with vertical displacements of the upper contact element when base oil is not used during a descent in the right-hand direction from the top of an circular arc of the lower contact element (a horizontal



(a) Comparison between vertical displacement (right axis) and contact voltage (left axis)

(b) Contact voltage (left axis) and difference in vertical displacement (right axis) of upper contact with and without Oil4

Fig. 7
Vertical displacement of upper contact and chattering
(load 0.2 N, with Oil 4, ±94mm/s).

displacement of about 0 mm in Fig. 7(b)). The curve showing a difference in displacements shows an elevation from about 1 μm up to 5 μm maximum at a voltage at which an electric current flow does not occur (indicated by a dotted arrow in Fig. 7(b)). Considering that the oil film thickness during the electric conduction was several nanometers, we suggest, from the Hamrock-Dowson equation [9] for the oil film thickness, that at an oil film thickness of about several tens to several hundred nanometers, an elevation of some micrometers shown in Fig. 7(b) will be exceeded even if the sliding speed is increased two times, the applied load is decreased by one-fifth, and the kinematic viscosity of base oil is increased 100 times. A consideration of the curve established when base oil is not used in Fig. 7(b) show that the top of a circular arc of the lower contact element assumes a horizontal position of about −2 mm. As indicated by an arrow in the figure, a vertical displacement of the circular arc top is about 11 μm. Analogously, considering that a vertical displacement of the circular arc top of the sliding surface of the lower contact element amounts to about 11 μm, shown by an arrow in Fig. 7(a), an elevation of some micrometers of the upper contact element appears over the circular arc top of the sliding surface of the lower contact element. In Fig. 7(a), the oil film grows thinner from 1.2 s to 1.3 s because a circular arc of the lower contact element pushes up the upper contact element. After 1.3 s, the presence of an oil film is enhanced because pushing up the lower contact element terminates at a level exceeding the top of a circular arc, and the pressure resistance by an oil film is increased. Therefore, we suggest that separation between contact elements increases by several micrometers. We also suggest that even in the case of low frequency of alternating movements, increasing the separation between contact elements of some tens to some hundred nanometers will be lower than a scale of some micrometers because of a protrusion on the sliding surface of the lower contact element. This phenomenon is a source of the chattering generation as well. In short, we conclude that sources of the chattering generation are (1) the sliding speed, an increase of the oil viscosity, and an increase of the oil film thickness under low-load conditions considered in Section 3.4 and (2) an increase of separation between contact elements by an increased pressure resistance of an oil film formed on the upper contact element considered in this section.

Preventing the chattering generation in sliding electrical contacts in the future requires an investigation of two problems presented as follows:

(1) It is necessary to determine quantitatively an increase of the oil film thickness and to compare the temporary frequency of the generation and the duration of the chattering and

the oil film thickness. It is necessary to analyze the effect of amounts of oil and grease applied in this connection.

(2) It is necessary to measure the accuracy of machining of the lower contact element to a nanometer scale to determine the effect exerted by the shape of the lower contact element on vertical displacement of the upper contact element.

4. CONCLUSION

Sliding experiments were performed using an apparatus simulating sliding electrical contacts at normal and low temperatures to clarify conditions under which the chattering generation occurs during the sliding of sliding electrical contacts and to establish reasons behind the chattering generation. Results obtained by performing experiments using base oil (PAO) and grease prepared by using base oil PAO and Li-12OHSt thickener have allowed us to clarify the following points.

(1) Chattering occurs more easily at higher sliding speeds.
(2) Chattering occurs more easily at a higher kinematic viscosity of base oils.
(3) Chattering duration is longer under low-load conditions.
(4) Reasons for the chattering generation is an increase of the thickness of oil films forming between contact elements under a high sliding speed, a high viscosity and a low-load conditions.

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