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Effect of grease type on abnormal vibration of ball bearing

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Abstract

The abnormal vibration of ball bearings lubricated with grease was studied. The test bearings were lubricated with three types of grease: Li soap/silicone oil grease, Na soap/mineral oil grease and Li soap/mineral oil grease. In the experiments, the axial-loaded ball bearings were operated at a constant rotational speed, and the vibration and the outer ring temperatures of the test bearings were measured. In addition, the shear stress and shear rate of the greases were measured by a rheometer. The experimental results showed that the abnormal vibration occurs on the test bearings lubricated with all three types of grease. Based on the experimental results, the generating mechanisms of the abnormal vibrations were discussed. From the discussions, it seems reasonable to conclude: (1) Li soap/silicone oil grease and Na soap/mineral oil grease both have a negative damping moment characteristic. The abnormal vibrations of the ball bearings lubricated with these greases are generated by the negative damping moment. (2) The abnormal vibration of the ball bearings lubricated with Li soap/mineral oil grease is generated by the decreasing positive damping moment of the grease due to the rising temperature.

1. Introduction

When grease-lubricated ball bearings are rotated, the outer ring sometimes vibrates with a large amplitude in the angular direction. This vibration is called abnormal vibration, and this has been a controversial issue for more than 30 years [1]. According to a previous study [1], this abnormal vibration occurs due to grease lubrication, and it is not observed in the case of oil lubrication. Also, it has been published that the occurrence of abnormal vibration differs according to the

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grease type and temperature. However, it is very difficult to analyze this problem experimentally and theoretically, there has been no sign of progress in the study of this problem.

Recently, the present authors measured the abnormal vibrations of ball bearings lubricated with Li soap/silicone oil grease and evaluated the relationship between the shear stress τ and shear rate $\dot{\gamma}$ of the grease by rheometer [2]. As a result, it was found that with Li soap/silicone oil grease, the τ tends to decrease rapidly after the rising $\dot{\gamma}$ passes a certain value. Then, it was inferred that the abnormal vibration of ball bearings lubricated with Li soap/silicone oil grease is self-excited vibration caused by this grease's property. As described above, this abnormal vibration is being clarified little by little, and there have been hardly any studies on the problem except on Li soap/silicone oil grease.

Under such circumstances, with the purpose of elucidating the cause of this abnormal vibration, the study was decided to perform from experimental and theoretical viewpoints. In the present study, the abnormal vibrations of a ball bearing lubricated with Li soap/silicone oil grease, Na soap/mineral oil grease and Li soap/mineral oil grease are treated. The effects of the types of grease on the occurrence of abnormal vibrations were studied experimentally.

2. Experiments

2.1. Test bearings and greases

For the test bearings, 6303 CM deep groove ball bearings were used. As the grease to lubricate the test bearings, Li soap/silicone oil grease, Na soap/mineral oil grease, and Li soap/mineral oil grease were used. Table 1 summarizes the compositions of the types of grease used and the base oil's properties. The grease amount was set to about 1.75 g.

2.2. Measurement of vibration and temperature

The methods to measure the vibration and the temperature of the outer ring are shown in Fig. 1. In the measurements, an axial load of 60.8 N was applied on the outer ring via two

Table 1
Composition of grease and properties of base oil

Grease	Thickener	Base oil			
		Type	Kinematic viscosity (cSt)		Atmospheric density (g/cm^3)
			40°C	100°C	15°C
Li soap/silicone oil grease	Li	Silicone oil	70.0	20.0	0.900
Na soap/mineral oil grease	Na complex	Mineral oil (paraffin base type)	109.0	9.7	0.870
Li soap/mineral oil grease	Li	Mineral oil (naphthen base type)	130.0	10.3	0.890

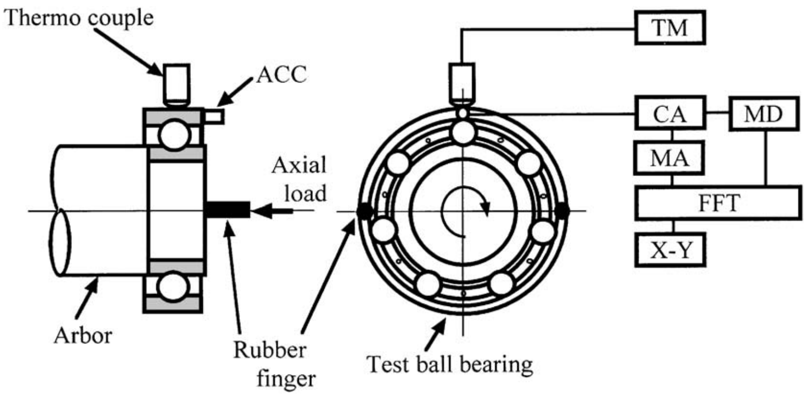

Fig. 1. Experimental apparatus and measuring system. ACC: accelerometer, CA: charge amplifier, MA: measuring amplifier, MD: MD recorder, FFT: FFT analyzer, $X-Y$: $X-Y$ plotter, TM: thermometer.

rubber-fingers, and the rotational speed of the inner ring was 1800 rpm. The measurements were carried out for 20 min using the Anderon-meter.

To measure the outer ring vibration, the vibratory acceleration was detected using an accelerometer mounted on the outer ring in the axial direction. The electric signal of the vibratory acceleration was amplified using a measuring amplifier, and the frequency analysis was performed using an FFT analyzer. To determine the time waveform of the vibratory acceleration, the electric signal from the charge amplifier was recorded on an MD recorder, and the recorded electric signal was displayed using the FFT analyzer and an $X-Y$ plotter.

To measure the outer ring temperature, the thermocouple was attached to the surface on the outer ring. It was planned so that the outer ring temperature at the initiation of rotation would be equal to the temperature of the measurement room.

2.3. Measurements of shear stress τ and shear rate $\dot{\gamma}$ of grease

The values of the shear stress τ and the shear rate $\dot{\gamma}$ of the grease were determined using a rotational parallel-disk type rheometer. In this measurement, the value of $\dot{\gamma}$ was varied from 0 to 1000 1/s, and the grease temperature was varied in several steps from 5°C to 45°C.

3. Experimental results

Fig. 2 shows an example of the normal and abnormal vibration spectra of Li soap/silicone oil grease. From Fig. 2, in the abnormal vibration, the vibratory acceleration level of the peak, f_1 is 40 dB higher and sharper than in the normal vibration. Also, in the abnormal vibration spectrum, there is a peak, f_2, at double the frequency of the peak, f_1. It was verified that this phenomena also occurs with Na soap/mineral oil grease and Li soap/mineral oil grease. In the present study, when the vibratory acceleration level increases more than 20 dB above the level immediately after the start of the experiment, it is considered to be abnormal vibration.

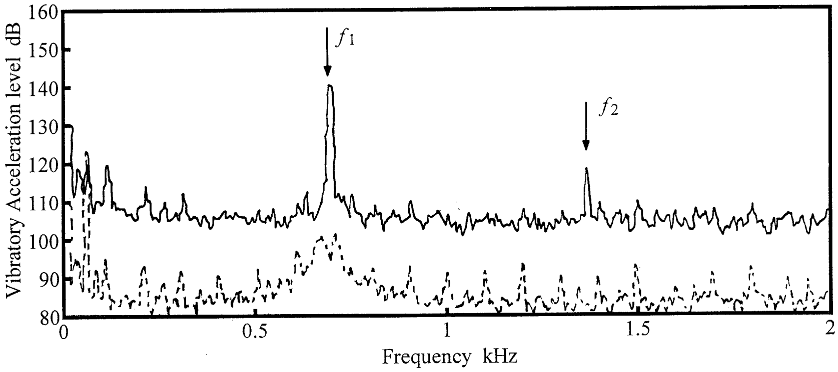

Fig. 2. Vibration spectra, Li soap/silicone oil grease, 0 dB = 1 μm/s^2: ………. normal vibration; ——— abnormal vibration.

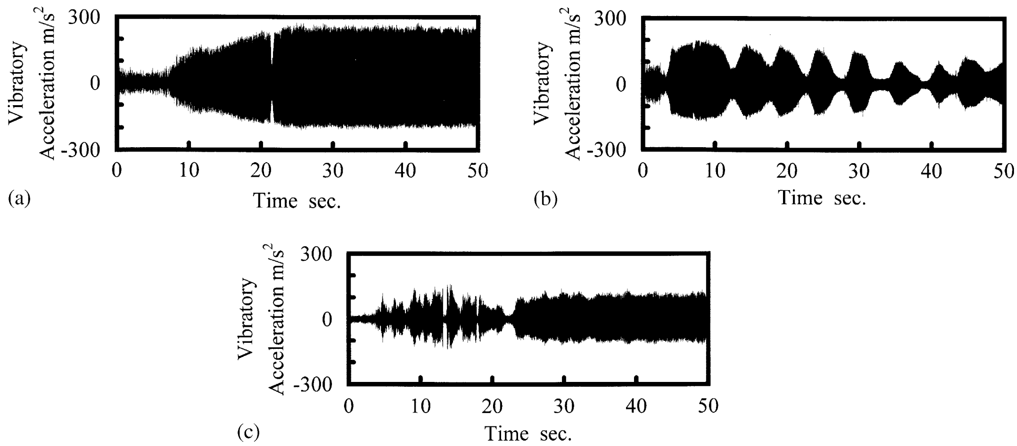

Fig. 3. Waveforms of vibration, room temperature = 20°C: (a) Li soap/silicone oil grease, (b) Na soap/mineral oil grease, (c) Li soap/mineral oil grease.

3.1. Waveforms of vibratory acceleration

Example waveforms of the vibratory acceleration when abnormal vibrations occur are shown in Fig. 3. In the case of Li soap/silicone oil grease shown in Fig. 3(a), once the abnormal vibration begins, the amplitude of the vibratory acceleration grows to a certain level, and then the abnormal vibration continues at that level for a long time. In the case of Na soap/mineral oil grease shown in Fig. 3(b), the abnormal vibration occurs, disappears and then recurs, and this is repeated, and the amplitude of the vibratory acceleration rapidly changes over time. In the case of Li soap/mineral oil grease shown in Fig. 3(c), the abnormal vibration occurs, disappears and then recurs, and this is repeated with short cycles several times, then the level stabilizes as with Li soap/silicone oil grease.

From these results, it was found that the abnormal vibration occurs in all three types of grease. And also the waveform of the abnormal vibration varies according to the grease type.

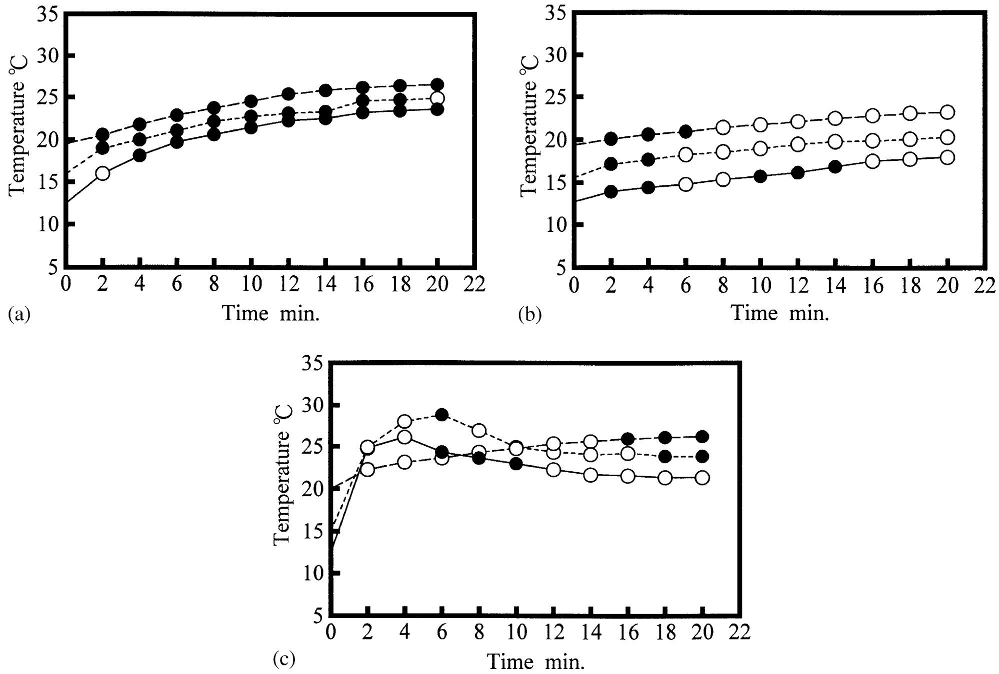

Fig. 4. Temperature of outer ring: (a) Li soap/silicone oil grease, (b) Na soap/mineral oil grease, (c) Li soap/mineral oil grease. ○ Normal vibration; ● abnormal vibration. ——— Room temperature = 10°C, ……… room temperature = 15°C, ---- room temperature = 20°C.

3.2. Temperature of outer ring

Fig. 4 plots the outer ring temperature vs. the rotation time. Open circles ○ indicate normal vibration and black circles ● indicate abnormal vibration. The normal vibration was verified always immediately after the start of rotation regardless of the grease used. In the case of Li soap/silicone oil grease shown in Fig. 4(a), the outer ring temperature increases over time and reaches equilibrium, and the abnormal vibration continues for a long time. In the case of Na soap/mineral oil grease shown in Fig. 4(b), the outer ring temperature gradually increases over time and then reaches equilibrium. The abnormal vibration occurs immediately after the start of rotation and does not continue for a long time. In the case of Li soap/mineral oil grease shown in Fig. 4(c), the outer ring temperature rapidly increases immediately after the start of rotation, peaks, then decreases gradually or reaches equilibrium. The abnormal vibration tends to occur only after the outer ring temperature peaks. Because it is believed that the grease temperature is approximately equal to the outer ring temperature [2], it is believed that the abnormal vibration in this grease occurs after the grease temperature peaks.

From these results, it was found that the relationship between the outer ring temperature and the rotation time differs according to the grease type. The grease temperature and type may also influence the abnormal vibration.

3.3. Shear stress and shear rate of grease

In a previous study [2], it was reported that, when the gradient of τ (shear stress)–$\dot{\gamma}$ (shear rate) curve of the grease is positive ($\mathrm{d}\tau/\mathrm{d}\gamma > 0$), the grease acts on the vibratory system as a positive damping moment, and when negative, a negative damping moment. Also, it is considered that, when Li soap/silicone oil grease is used, the abnormal vibration occurs due to the grease characteristics of $\mathrm{d}\tau/\mathrm{d}\dot{\gamma} < 0$. In this respect, for the three types of grease, the $\tau - \dot{\gamma}$ curves shown in Fig. 5 were obtained by the method described in 2.3. In Fig. 5, $(\dot{\gamma}_1(T), \tau_{mp}(T))$ is the maximum point, and $(\dot{\gamma}_2(T), \tau_{ip}(T))$ is the inflection point of $\tau - \dot{\gamma}$ curve at some T. The relationships between $\dot{\gamma}$ and $\mathrm{d}\tau/\mathrm{d}\dot{\gamma}$ are obtained from the $\tau - \dot{\gamma}$ curve, and are shown in Table 2. From Fig. 5 and Table 2, the following features can be found in the three types of grease.

(a) *Li soap/silicone oil grease*: The value of τ rapidly increases from 0 Pa as $\dot{\gamma}$ increases, and τ reaches its maximum value. In this range, $\mathrm{d}\tau/\mathrm{d}\dot{\gamma} > 0$. Next, when $\dot{\gamma}_1(T) \leqslant \dot{\gamma} < \dot{\gamma}_2(T)$, then $\mathrm{d}\tau/\mathrm{d}\dot{\gamma} < 0$. Furthermore, when $\gamma_2(T) \leqslant \gamma$, then $\mathrm{d}\tau/\mathrm{d}\dot{\gamma} < 0$ or $\fallingdotseq 0$. There is almost no change due to the grease temperature in the $\tau - \dot{\gamma}$ curve.

(b) *Na soap/mineral oil grease*: When $0 \leqslant \dot{\gamma} < \dot{\gamma}_1(T)$, then $\mathrm{d}\tau/\mathrm{d}\dot{\gamma} > 0$, and when $\dot{\gamma}_1(T) \leqslant \dot{\gamma} < \dot{\gamma}_2(T)$, then $\mathrm{d}\tau/\mathrm{d}\dot{\gamma} > 0$. Furthermore, when $\dot{\gamma}_2(T) \leqslant \dot{\gamma}$, then $\mathrm{d}\tau/\mathrm{d}\dot{\gamma} > 0$. When $\dot{\gamma}_2(T) \leqslant \dot{\gamma}$, the value of τ with respect to $\dot{\gamma}$ varies greatly according to the grease temperature T. And, there are no clear relationships between the value of τ and T.

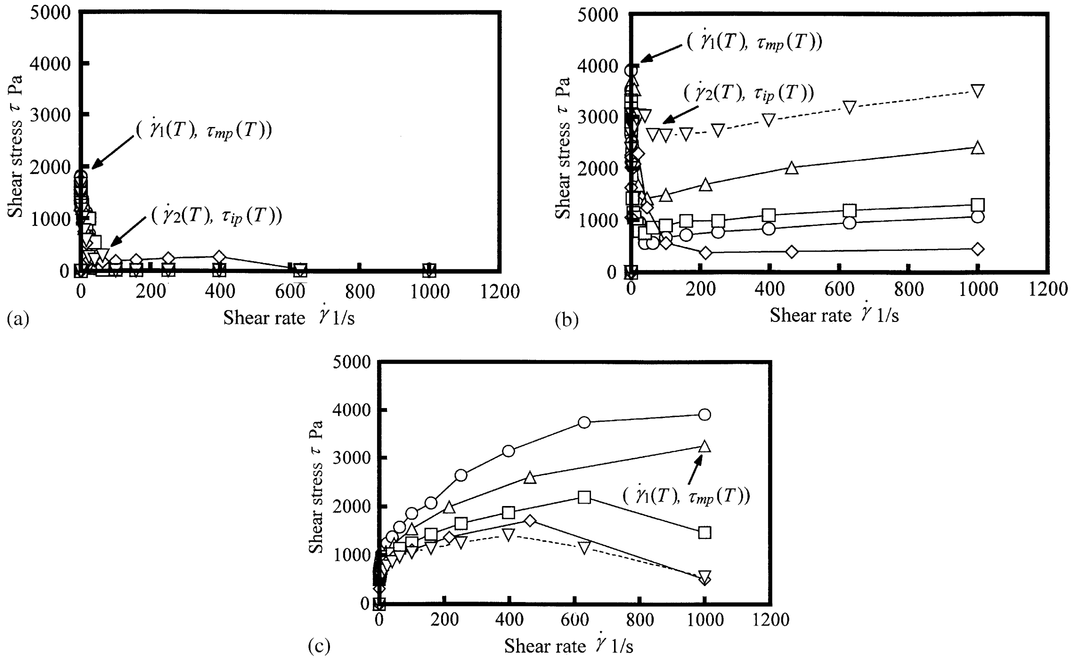

Fig. 5. $\tau - \dot{\gamma}$ curves of grease: (a) Li soap/silicone oil grease, (b) Na soap/mineral oil grease, (c) Li soap/mineral oil grease. —○— Grease temperature = 10°C; —△— grease temperature = 15°C; —□— grease temperature = 20°C; —◇— grease temperature = 25°C; ⋯ ▽ ⋯ grease temperature = 30°C.

Table 2
Relationship between $\dot{\gamma}$ and $d\tau/d\dot{\gamma}$

Grease	$0 \leqslant \dot{\gamma} < \dot{\gamma}_1(T)$	$\dot{\gamma}_1(T) \leqslant \dot{\gamma} < \dot{\gamma}_2(T)$	$\dot{\gamma}_2(T) \leqslant \dot{\gamma}$
Li soap/silicone oil grease	$d\tau/d\dot{\gamma} > 0$	$d\tau/d\dot{\gamma} < 0$	$d\tau/d\dot{\gamma}0$ $d\tau/d\dot{\gamma} < 0$
Na soap/mineral oil grease	$d\tau/d\dot{\gamma} > 0$	$d\tau/d\dot{\gamma} < 0$	$d\tau/d\dot{\gamma} > 0$
Li soap/mineral oil grease	$d\tau/d\dot{\gamma} > 0$	$d\tau/d\dot{\gamma} < 0$[a] $(\dot{\gamma}_1(T) \leqslant \dot{\gamma})$	

[a] When the temperature is above 20°C.

(c) *Li soap/mineral oil grease*: When $0 \leqslant \dot{\gamma} < \dot{\gamma}_1(T)$ then $d\tau/d\dot{\gamma} > 0$. Compared with the other two types of grease, the range of $d\tau/d\dot{\gamma} > 0$ is wide. Unlike the other two types of grease, there is no inflection point in the $\tau - \dot{\gamma}$ curve. And when T is 20°C or more, there are the range of $d\tau/d\dot{\gamma} > 0$. If $\dot{\gamma}$ is same, the τ becomes small when grease temperature is higher.

From the above, it was shown that the $\tau - \dot{\gamma}$ curve of the grease varies according to the grease type.

4. Analyses and discussions

From the experimental results, it was verified that the abnormal vibration is related to the temperature and the grease type. Here, the relationship between the abnormal vibration and the EHL grease film will be evaluated.

4.1. EHL grease films

Aihara and Dowson [3] found that there is the following relationship between the EHL grease film thickness h_g and the base oil film thickness h_b:

$$h_g = 0.5h_b \sim 0.7h_b. \tag{1}$$

The central base oil film thicknesses $h_{ci,o}$ (the subscripts i and o refer to the inner and outer rings, respectively) were calculated by the equation of Hamrock–Dowson [4]. In the equation of Hamrock–Dowson, the oil film thickness is related to the load, the material characteristic and the entrainment velocity. For the three types of grease, the EHL grease film thicknesses $h_{i,o}$ were calculated from Eq. (1). In this calculation, it was assumed that $h_{i,o} = 0.6h_{ci,o}$. This calculation results are shown in Fig. 6. From Fig. 6, $h_{i,o}$ decrease as the temperature increases, and h_o is slightly greater than h_i, regardless of the grease type. Compared with Li soap/silicone oil grease (Fig. 6(a)), $h_{i,o}$ decrease extremely as the temperature increases with both Na soap/mineral oil grease (Fig. 6(b)) and Li soap/mineral oil grease (Fig. 6(c)). The values of h_i and h_o are approximately equal to each other. To facilitate the analysis, $h_{i,o}$ use the average value $h(= (h_i + h_o)/2)$.

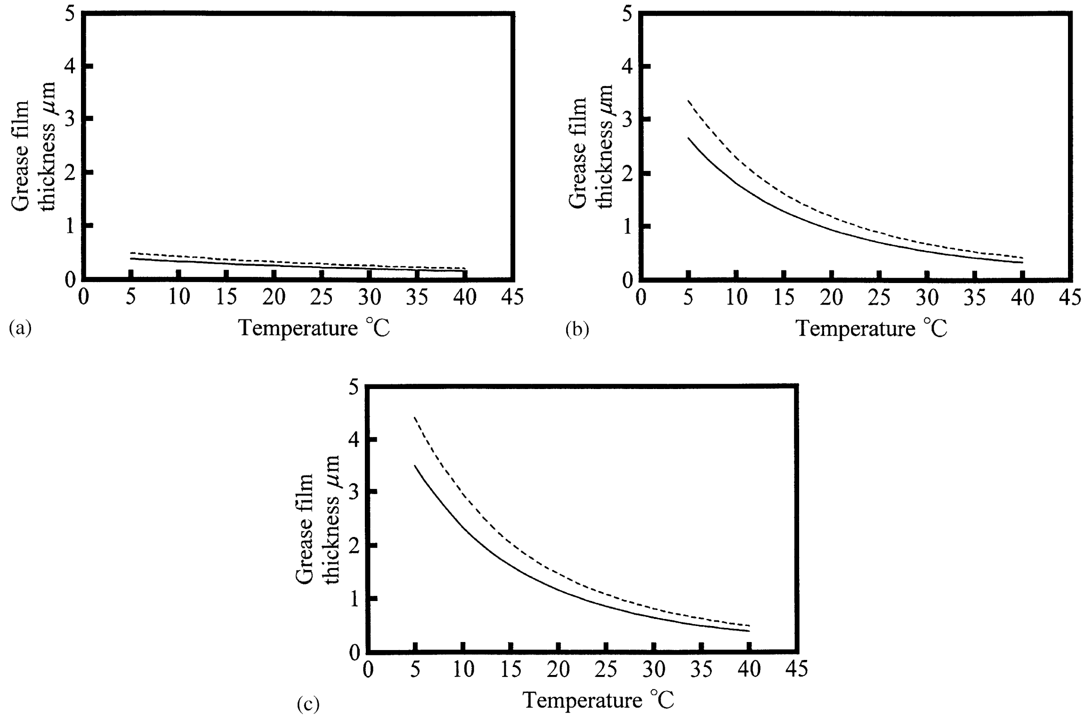

Fig. 6. EHL grease film thickness: (a) Li soap/silicone oil grease, (b) Na soap/mineral oil grease, (c) Li soap/mineral oil grease. ——— h_i; ……… h_o .

4.2. Sliding velocities of contact areas between inner and outer rings and balls

4.2.1. Velocities of inner and outer rings and balls

Fig. 7 shows the velocities of the outer and the inner rings and a ball when the outer ring vibrates in the angular direction. In Fig. 7, α is the contact angle. V_o is the actual velocity of the contact area between the outer ring and the ball. V_b is the actual velocity of the center of the ball. V_i is the actual velocity of the contact area between the inner ring and the ball. When no sliding occurs on both contact areas, the theoretical velocity V_b' of the center of the ball must be as follows:

$$V_b' = (V_i + V_o)/2. \tag{2}$$

In the previous study [2], V_b does not agree with V_b'. That is, when the outer ring vibrates in the angular direction, the alternate sliding occurs on both contact areas between the inner and outer rings and the ball.

4.2.2. When sliding occurs only on contact areas between an inner ring and balls

When the sliding occurs only on the contact area between the inner ring and a ball, the theoretical sliding velocity V_i' on the contact area between the inner ring and the ball is as shown

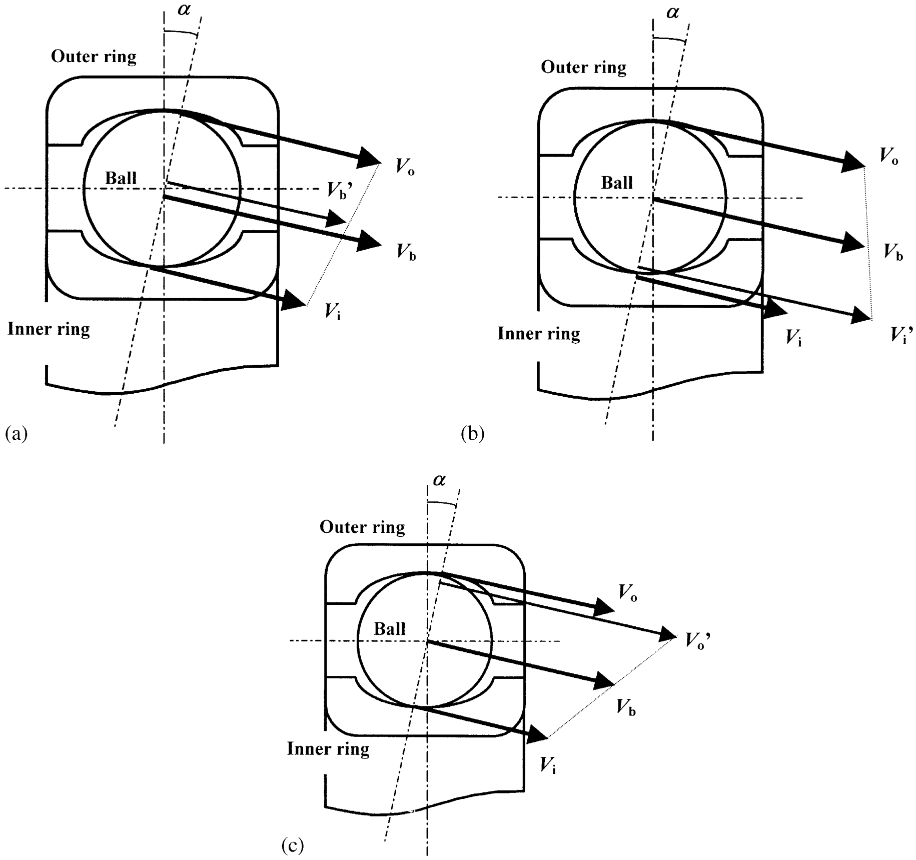

Fig. 7. Sliding velocity: (a) velocities of outer ring, inner ring and ball, (b) case of inner ring slide, (c) case of outer ring slide.

in Fig. 7(b). V_i' can be given by the following equation:

$$V_i' = 2V_b - V_o. \tag{3}$$

From Eqs. (2) and (3), the absolute value of the sliding velocity V_{si} of the contact area between the inner ring and the ball is given by the following equation:

$$V_{si} = \left|V_i' - V_i\right| = |2V_b - V_o - V_i| = |2V_b - (V_i + V_o)| = 2\left|V_b - V_b'\right|. \tag{4}$$

4.2.3. When sliding occurs only on contact areas between an outer ring and balls

When the sliding occurs only on the contact area between the outer ring and a ball, the theoretical sliding velocity V_o' of the contact area between the outer ring and the ball is as shown in Fig. 7(c). V_o' can be given by the following equation:

$$V_o' = 2V_b - V_i. \tag{5}$$

From Eqs. (2) and (5), the absolute value of the sliding velocity V_{so} of the contact area between the outer ring and the ball is given by the following equation:

$$V_{so} = \left|V_o' - V_o\right| = |2V_b - V_i - V_o| = |2V_b - (V_i + V_o)| = 2\left|V_b - V_b'\right|. \tag{6}$$

4.2.4. When sliding occurs on both contact areas between inner and outer rings and balls

Sections 4.2.2 and 4.2.3 discuss the case that the sliding occurs on either the contact areas between the inner and outer rings and a ball. In reality, the sliding occurs at both contact areas [2].

When it is supposed that the sliding occurs at both contact areas, V_{si}^* and V_{so}^* are the absolute values of the sliding velocity on the contact areas between the inner and outer rings and the ball, respectively. From Eqs. (4) and (6), it is considered that the values of V_{si}^* and V_{so}^* are within the range of 0 to $2|V_b - V_b'|$. However, it is difficult to the analytically determine the values of V_{si}^* and V_{so}^*. In this respect, it is assumed in the present study that the values of V_{si}^* and V_{so}^* can be expressed by V_s given in the following equation:

$$V_{si}^* = V_{so}^* = |V_b - V_b'| = V_s. \tag{7}$$

4.3. Relationship between sliding velocities and angular vibration of outer ring

In order to assess the relationship between the absolute value V_s of the sliding velocity and the angular velocity $\dot{\theta}$ of the outer ring, V_o, V_i and V_b were measured [2]. The value of V_s was obtained using Eqs. (2) and (7). Fig. 8 shows the relationship between V_s and $\dot{\theta}$. From Fig. 8, the temperature exerts almost no influence on V_s. The involution approximate straight line to the experimental results and its equation are given in Fig. 8. The relationship between V_s and $\dot{\theta}$ given by the following equation regardless of the temperature:

$$V_s = a\dot{\theta}^b, \tag{8}$$

where a and b are a coefficient and an index, respectively, they are determined from the type of grease.

4.4. Relationship between angular vibration of outer ring and shear rate of EHL grease films

When the outer ring vibrates in the angular direction, the sliding occurs at both contact areas between the inner and outer rings and a ball. For this reason, the EHL grease films between the inner and outer rings and the ball are sheared. The shear rate $\dot{\gamma}(T)$ of these EHL grease films at some T can be given by the following equation:

$$\dot{\gamma}(T) = V_s/h(T). \tag{9}$$

When Eq. (8) is substituted into Eq. (9), the following equation is obtained:

$$\dot{\gamma}(T) = a\dot{\theta}^b/h(T). \tag{10}$$

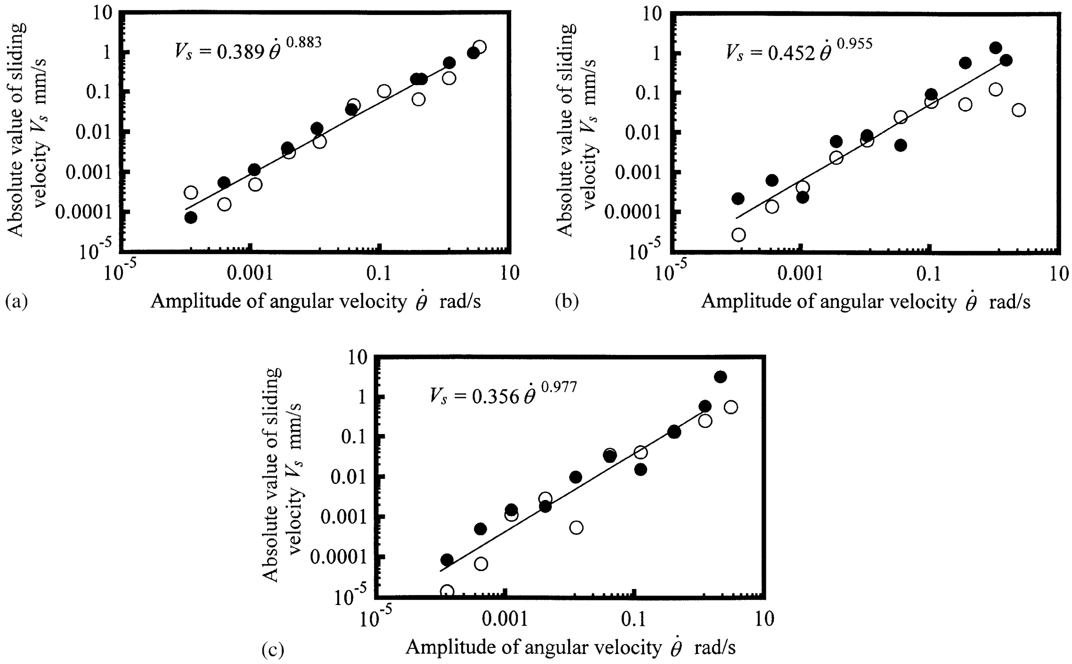

Fig. 8. Absolute values of sliding velocity and amplitude of angular velocity: (a) Li soap/silicone oil grease, (b) Na soap/mineral oil grease, (c) Li soap/mineral oil grease. ○ Room temperature = 10°C; ● room temperature = 25°C.

4.5. *Relationship between properties of EHL grease films and abnormal vibration*

The relationship between the conditions of the vibration, the outer ring temperature (the grease temperature) T, the angular velocity $\dot{\theta}$ of the outer ring, and the $\mathrm{d}\tau/\mathrm{d}\dot{\gamma}$ of the grease's $\tau - \dot{\gamma}$ curve is summarized in Fig. 9. Fig. 9 has been given as follows: first, the value of $\dot{\theta}$ with respect to $\dot{\gamma}$ was calculated from Eq. (10). Then, $\mathrm{d}\tau/\mathrm{d}\dot{\gamma}$ with respect to $\dot{\gamma}$ was calculated from Fig. 5. Furthermore, these calculations were repeated within the temperature T range of 10–40°C. Based on the experimental results, the normal and abnormal vibrations were plotted as the open circles ○ and the black circles ●, respectively. From Fig. 9, the following relationships can be found between the three types of grease and the abnormal vibration:

(a) *Li soap/silicone oil grease*

(i) In the normal vibration, the $\mathrm{d}\tau/\mathrm{d}\dot{\gamma}$ is negative. Therefore, during the normal vibration, the grease acts on the vibratory system as a negative damping moment. The amplitude of the vibration therefore increases over time, thereby triggering the abnormal vibration.

(ii) In the abnormal vibration, the $\mathrm{d}\tau/\mathrm{d}\dot{\gamma}$ is positive or negative. Therefore, when the abnormal vibration occurs, grease acts on the vibratory system as a positive or a negative damping moment. For this reason, the amplitude of the abnormal vibration, depending on the magnitude of the damping moment, could increase, be roughly stable, or decrease.

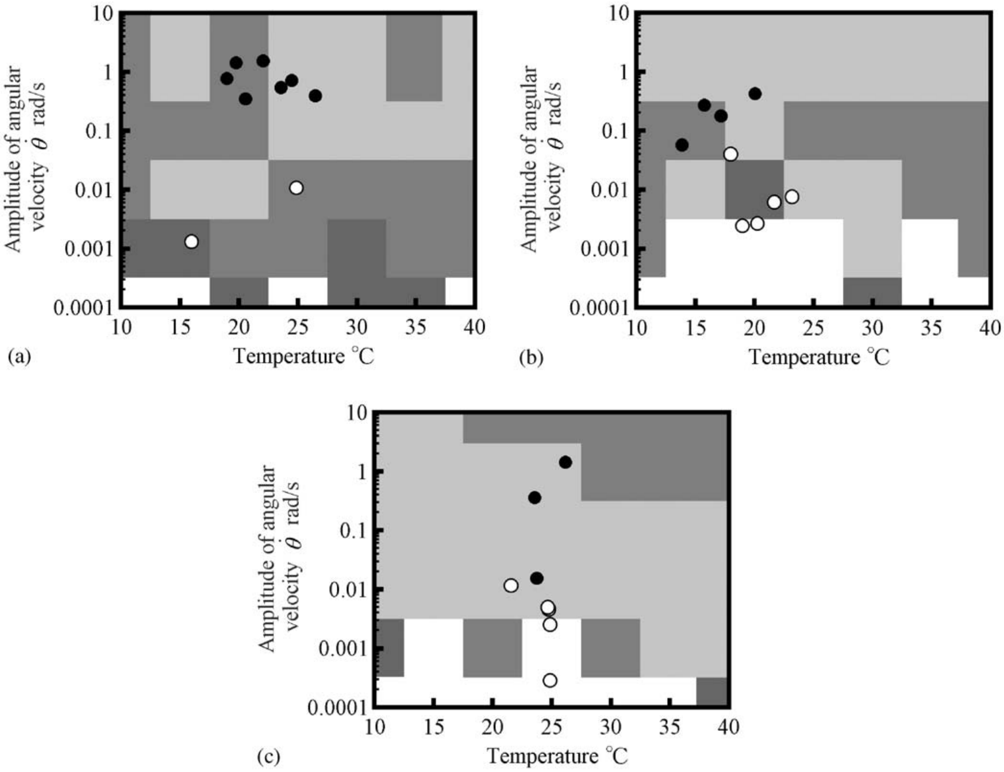

Fig. 9. Occurrence of abnormal vibration: (a) Li soap/silicone oil grease, (b) Na soap/mineral oil grease, (c) Li soap/mineral oil grease. ○ Normal vibration; ● abnormal vibration. □ $d\tau/d\dot{\gamma} \geqslant 100$ Pa s; $0 \leqslant d\tau/d\dot{\gamma} < 100$ Pa s; $-100 \leqslant d\tau/d\dot{\gamma} < 0$ Pa s; $d\tau/d\dot{\gamma} \leqslant -100$ Pa s.

(b) *Na soap/mineral oil grease*

(i) In the normal vibration, the $d\tau/d\dot{\gamma}$ is positive or negative. When it is $d\tau/d\dot{\gamma} < 0$, the grease acts on the vibratory system as a negative damping moment. The amplitude of the vibration increases over time, therefore, the abnormal vibration may occur. On the other hand, when $d\tau/d\dot{\gamma} > 0$, grease acts on the vibratory system as a positive damping moment. Thus, the amplitude of the vibration decreases over time, and the abnormal vibration does not occur.

(ii) In the abnormal vibration, the $d\tau/d\dot{\gamma}$ is positive or negative. Therefore, when the abnormal vibration occurs, grease acts on the vibratory system as a positive or a negative damping moment. As a result, the amplitude of the abnormal vibration further increases over time, or it decreases.

(iii) The $d\tau/d\dot{\gamma}$ is varies extensively depending on the change of the grease temperature as shown in Fig. 5(b). During rotation, the grease temperature gradually increases over time and then reaches equilibrium as shown in Fig. 4(b). Therefore, the sign and the magnitude of the damping moment vary extensively during rotation. For this reason, the abnormal vibration does not last for a long time, and it repeatedly appears and disappears as shown in Fig. 3(b).

(c) *Li soap/mineral oil grease*

(i) In the normal vibration, the $d\tau/d\dot{\gamma}$ is positive. Therefore, during normal vibration, grease acts on the vibratory system as a positive damping moment. For this reason, the occurrence of the abnormal vibration cannot be explained by the negative damping moment of the grease.
(ii) If $\dot{\gamma}$ is the same, the $d\tau/d\dot{\gamma}$ is smaller when the temperature is higher as shown in Fig. 5(c). During rotation, the grease temperature increases after the start of rotation as shown in Fig. 4(c), and this means that $d\tau/d\dot{\gamma}$ decreases over time from the start of rotation. As shown in Fig. 7(c), the $d\tau/d\dot{\gamma}$ is always positive during rotation. This decrease of the $d\tau/d\dot{\gamma}$ over time means that the positive damping moment of the grease gradually decreases over time. In this way, the positive damping moment of the grease gradually decreases over time. As a result, the amplitude of the vibration increases and the abnormal vibration may occur.
(iii) When the abnormal vibration occurs, the grease temperature decreases as shown in Fig. 4(c). As shown in Fig. 5(c), the $d\tau/d\dot{\gamma}$ is smaller when the temperature is higher. This means that the $d\tau/d\dot{\gamma}$ gradually increases over time. Therefore, in the abnormal vibration, the positive damping moment gradually increases over time, and it is believed that the amplitude of the vibration then decreases over time.
(iv) As described above, the positive damping moment of the grease gradually increases or decreases over time. Depending on how much it increases or decreases, it is believed that the abnormal vibration continues, occurs and disappears and might recur as shown in Fig. 3(c).

Furthermore, the theoretical analysis should be performed on the relationship of the $d\tau/d\dot{\gamma}$ and the damping moment and the abnormal vibration.

5. Conclusions

Based on the experimental results, the analyses and discussions as given above, the following conclusions have been reached:

(1) The abnormal vibration occurs in all cases, i.e., regardless of whether Li soap/silicone oil grease, Na soap/mineral oil grease or Li soap/mineral oil grease is used.
(2) In the ball bearings lubricated with Li soap/silicone oil grease or Na soap/mineral oil grease, It is believed that the abnormal vibration occurs when the grease acts on the vibratory system as a negative damping moment during the normal vibration.
(3) In the ball bearings lubricated with Li soap/mineral oil grease, the abnormal vibration occurs because a positive damping moment of the grease gradually decreases over time and it acts on the vibratory system.

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