Grease Lubrication Technology for Reducing Noise in Rolling Bearings

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We have investigated the effect of grease properties and composition on the acoustic performance of bearings, from two aspects that differ from conventional practices. The first of these aspects is the effect of the mechanical properties of thickeners, with a focus on the damping characteristic of thickeners. The second investigated aspect is the effect of the aggregate state of the thickeners on the nanometerscale. The results of this investigation showed that the acoustic value of a bearing can be lowered by using a thickener with a small Young's modulus and excellent damping performance, or by increasing the expansion of the thickener using base oil for which the HSP value is low or for which the fractal index is small.

***Key Words**: grease, grease noise, Young's modulus, nanometerscale structure, SAXS*

1. Background

The shift to electric vehicles and electronic control of vehicles is predicted to gain further momentum moving forward in an effort to minimize the use of fossil fuels and improve fuel efficiency. Exemplified by the fuel cell and electric motor system that substitute the engine, the systems which accompany electric vehicles are also predicted to shift towards electrification in order to eliminate the engine as a power source. Motors are already being used even inside vehicles in places such as the windscreen wipers, air conditioning, power windows and power seats. There is even an increase in cars that use engines which are equipped with an idling stop function and it is predicted that the quietness of a vehicle interior will be further enhanced. For this reason, it is assumed that the acoustic performance of the rolling bearing used in various motors will become a key focus.

To date, studies have been conducted into the effect of grease composition and properties on the acoustic characteristics of rolling bearings and many research reports and presentations have been delivered. For example, Igarashi and company investigated the effect of the grease base oil viscosity and thickener fiber size on bearing acoustic characteristics and demonstrated that the greater the base oil viscosity, or the smaller the fiber size, the more noise is reduced1). Kobayashi focused on Bingham flow, which is a flow behavior specific to grease, and has demonstrated that abnormal vibration can be caused by the damping ability of grease being smaller than the Newtonian fluid2). Komiya investigated the relationship between base oil viscosity and penetration and the size of the solid material, clarifying that the lower the base oil viscosity or the greater the penetration, the greater the noise created by thickener became3). Moreover, Endo and company have discussed the smoothness of thickener membrane from the thickness profile of EHL (elasto-hydrodynamic lubrication) thickener membrane and concluded that grease which forms a smooth thickener membrane has a high level of quietness4). Moreover, Mikami has investigated from the perspective of acoustic life, whereby the acoustic characteristic is maintained for a long period of time, and elucidated that increasing the amount of thickener is effective in improving acoustic life and, as this slows down the softening of grease, it helps to minimize expulsion of grease from the rolling face5).

As introduced above, many studies have been conducted to date, however there is a lack of studies which focus on the effect of the mechanical properties of thickeners on bearing acoustic characteristics and the effect of the aggregate state of the thickeners and crystalline structure in the grease at a molecular level. However, thanks to the advancements in measurement and analysis technologies, it has now become possible to measure the mechanical properties of thickeners and predict the aggregate state and crystalline structure at a molecular level. This study examines the mechanical properties of thickener at a nanoscale level, as well as the correlation between structural state and bearing acoustic characteristics and proposes a method to reduce bearing noise.

2. Test Method

2. 1 Test Grease

2. 1. 1 Effect of the Mechanical properties of the Thickener on Acoustic Value

Table 1 shows the compositions and properties of the test grease used in this study. Three types of urea grease with identical base oils and isocyanates and differing molecular structures with only the amine composition changed were prepared. A synthetic hydrocarbon oil, Poly-Alpha-Olefin (PAO) was used as the base oil, as it is popular as a highly-functional grease base oil. Due to the current high demand for the base oil kinematic viscosity to contribute to reducing torque loss in rolling bearings and the expectation that thickener may have a notable effect on the acoustic characteristic, PAO6, which is classified as having low viscosity, was used as the rolling bearing grease. The urea-compound serving as the thickener was made by reacting isocyanate and amine in base oil to compound them. For this study, 4,4'-methylenediphenyl diisocyanate (MDI) was used as the isocyanate, while three types of amines were used; monocycle alkylamine, straight-chained alkylamine and aromatic alkylamine. In order to eliminate the effect of the thickener's secondary aggregate on bearing acoustic value, the thickener was finely dispersed by rolling.

2. 1. 2 Effect of Thickener Crystal Higher-Order Structure

Next, in order to investigate the effect of thickener higher-order structure and base oil polarity on bearing acoustic value, grease using base oils with differing chemical compositions was prepared and evaluated. The chemical composition of PAO is carbon and hydrogen and it is non-polar, meaning there is no polarization of electrons within the molecules. Meanwhile, base oils containing ester bond and ether bond are polar because the electrons in the molecules are polarized due to the presence of oxygen atoms with unshared electron pair or unsaturated bonds. **Table 2-1** shows the compositions and properties of test grease which uses non-polar PAO as the base oil, while **Table 2-2** shows the compositions and properties of test grease which uses polar alkyldiphenylether (ADE) and polyolester (POE) as base oil. Regarding the amine type, grease made from a single amine and a combination of two types of amines was prepared and evaluated. The amine molar ratio was 1:1. As shown in **Table 1**, the thickener amount was kept consistent at 15 mass% and the thickener was finely dispersed by rolling in order to eliminate the effect of the thickener's secondary aggregate particles on bearing acoustic value.

2. 2 Test Conditions

2. 2. 1 Bearing Acoustic Characteristics

Bearing noise were evaluated based on bearing vibrational acceleration. **Table 3** shows the measurement method of bearing vibrational acceleration (hereinafter bearing acoustic characteristics). 0.69 grams of test grease was injected into the bearing (62022RU) then sealed inside with a non-contact rubber seal. Next, the bearing was loaded into the spindle of a measurement device and subjected to an axial load of 20 N. When the inner ring was rotated at 1 800 min^{-1}, the vibrational acceleration in the radial direction of the bearing outer ring (which is at its maximum when rotation starts) was measured using a piezoelectric accelerometer.

Table 1 Compositions and properties of test grease ①

		Aliphatic	Alicyclic	Aromatic
Thickener	Isocyanate	MDI		
	Amine	Alicyclic amine ODA	Aliphatic amine CHA	Aromatic amine pTD
Base oil		PAO6		
Thickener amount, mass%		15		
Base oil kinematic viscosity, mm^2/s (40℃)		30		
Worked penetration (25℃)		329	256	356
Average particle size, μm		2.41	2.81	1.34

MDI：4,4'-methylenediphenyl diisocyanate ODA：Octadecylamine CHA：Cyclohexylamine
pTD：p-Toluidine PAO：Poly-Alpha-Olefin

Table 2-1 Compositions and properties of test grease ② (Non-polar base oil)

Symbol			A	B	C	D	E	F	G	H
Thickener	Isocyanate		MDI							
	Amine	ODA	○	–	–	–	○	–	○	–
		OTA	–	○	–	–	–	–	○	○
		CHA	–	–	○	–	○	○	–	–
		pTD	–	–	–	○	–	○	–	○
Base oil			PAO6							
Thickener amount, mass%			15							
Base oil kinematic viscosity, mm^2/s (40℃)			30							

OTA：Octylamine

Table 2-2 Compositions and properties of test grease ② (Polar base oil)

Symbol			I	J	K	L	M	N	O
Thickener	Isocyanate		MDI						
	Amine	ODA	○	–	○	○	–	○	○
		OTA	–	–	–	–	–	–	○
		CHA	–	–	○	–	–	○	–
		pTD	–	○	–	–	○	–	–
Base oil			ADE			POE			
Thickener amount, mass%			15			15			
Base oil kinematic viscosity, mm^2/s (40℃)			32.3			30			
Worked penetration (25℃)			337	315	169	377	328	203	272

ADE：Alkyldiphenylether　POE：Polyolester

Table 3 Test condition of vibrational acceleration of bearings

Item	Condition
Bearing model no. I.D.×O.D.×w, mm	62022RU (Non-contact rubber seal) 15×35×11
Amount of grease, g	0.69
Axial load, N	20
Rotational speed, min^{-1}	1 800
Measurement time, s	5

2. 2. 2 Preparation Method of Test Samples for Measurement of Young's Modulus of the Thickener

The samples used to measure the Young's modulus of the thickeners were prepared using the two methods shown in **Table 4-1** and **Table 4-2**. **Figure 1** provides schematic diagrams for the respective preparation methods. Preparation Method A involves first dispersing the grease in solvent then isolating the thickener through a process of suction filtration and solvent cleaning. The thickener is then placed in an aluminum case and pressed down in accordance with the conditions shown in **Table 4-1**. For preparation Method B, after isolating the thickener in the same way as Method A, thickener was adhered to the bottom of a mold, phenolic resin placed over the top, then the resin was embedded through a process of heat compression. It is believed that, in the case of Method A, the sample is not effected by temperature but it is effected by being compressed. Meanwhile, in the case of Method B, it is believed the sample is not effected by pressure (as the pressure during compression is relatively low) but is effected by temperature.

Table 4-1 Conditions of preparation of samples for measurement of Young's modulus (Method A)

Item	Condition
Applied load, N	19.6
Compression time, s	60
No. of compressions, times	2

Table 4-2 Conditions of preparation of samples for measurement of Young's modulus (Method B)

Item	Condition
Resin composition	Phenolic resin
Heating temperature, ℃	130
Compression pressure, MPa	1.5
Compression time, s	900

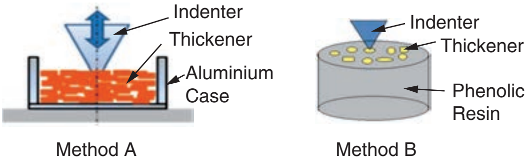

Fig. 1 Preparation method of samples for measurement of Young's modulus

2. 2. 3 Conditions for Young's Modulus Measurement

Table 5 gives the conditions for measuring the Young's modulus of thickeners. The Young's modulus was found by using a nanoindenter on the measurement device, applying an indentation load as shown in **Table 5**, and then observing the inclination of the unloading curve when the load is removed. The indentation load was determined after taking a preliminary measurement to ensure the indentation depth would be less than one-tenth the thickness of the thickener being measured.

Table 5 Measurement conditions for Young's modulus of thickeners

Item	Condition
No. of measurement points	4〜6
Indentation load, μN	500
Loading time, s	5
Unloading time, s	3

2. 2. 4 Aggregate State of Thickener

The aggregate state of the thickener was observed using two different methods depending on the scale. First, the aggregate state at micrometer scale involved using a polarization microscope to observe grease, which had been thinned between the slide glass and cover glass, at a magnification of 500 and thresholding the obtained image to find the number of aggregate particles 1 μm or larger in size. Meanwhile, the aggregate state at nanometerscale was measured using the small angle X-ray scattering (SAXS) technique. As **Fig. 2** shows, the SAXS method involved illuminating grease sealed in a Polyimide tube with a 1.5 keV Xray and measuring at a camera length of 4.5 m. The SAXS spectrum was fitted on the unified model as shown in (1) to obtain the radius of gyration and fractal index[6].

$$I(q) = G\exp(-q^2 R_g{}^2/3) + B\left\{\frac{[\mathrm{erf}(\frac{qRg}{\sqrt{6}})]^3}{q}\right\}^P \quad (1)$$

q : Scattering vector, R_g : Radius of gyration,
P : Fractal index, G, B : Coefficient

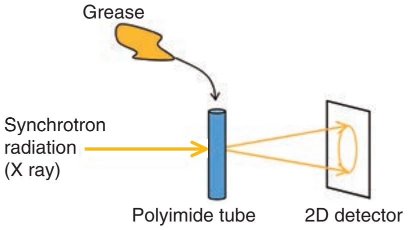

Fig. 2 Measurement method of SAXS

3. Results

3. 1 Bearing Acoustic Value

Table 6-1 shows the measurement results of acoustic characteristics of bearings using test grease ①, for which the effect of mechanical properties was evaluated. **Table 6-2** shows the measurement results of acoustic characteristics of bearings using test grease ②, for which the effect of thickener higher-order structure and base oil polarity were evaluated. **Table 6-1** gives the acoustic characteristics directly after rotation has begun and after stabilization. The table also includes the average size of thickener particles measured using a laser diffraction particle size distribution analyzer.

Comparing the acoustic values for test grease ① at the start of rotation and after stabilization shows that the acoustic value is lower after stabilization due to the thickener being miniaturized by mechanical shearing between the rolling element and raceway. Moreover, all of the test grease used for this study had a common thickener amount of 15 mass% therefore, although the worked penetration differed between the grease, it is believed that the state of grease adhesion between the rollers and raceway at the start of rotation was not largely affected by worked penetration therefore this evaluation included comparisons with the bearing acoustic value at the start of rotation. For this reason, only the bearing acoustic value at the start of rotation is given for test grease ②.

For test grease ①, the bearing acoustic value differed depending on the amine composition of the thickener, with the bearing using the aliphatic diurea thickener having the smallest acoustic value, followed by the bearing using the alicyclic diurea, then finally the bearing using the aromatic diurea. Previous research has claimed that there is a correlation between the size of thickener particles and bearing acoustic value, with the latter increasing in proportion to the former1) however this evaluation did not find any such correlation.

For test grease ②, the bearing acoustic values for the non-polar PAO with thickeners compositions of alicyclic, aliphatic and aromatic single amines were in good agreeance with those of test grease ①, thereby confirming reproducibility. The acoustic value of the bearing using non-polar PAO with the amine combination was reduced if either ODA or pTD was used in combination with CHA, compared to the acoustic value of the bearing when CHA was used in isolation. On the other hand, the bearing acoustic value of OTA and ODA in combination is close to the bearing acoustic value of OTA in isolation, and the bearing acoustic value of OTA and pTD in combination is close to the bearing acoustic value of pTD in isolation, therefore the bearing acoustic value did not decrease as a result of combination.

The effect of changing base oil polarity on bearing acoustic value differed depending on base oil composition, amine composition and amine combination, and no clear trend was apparent.

Table 6-1 Measurement results of acoustic characteristics of bearings (Test grease ①)

	Alicyclic	Aliphatic	Aromatic
Bearing acoustic value at initial rotation, G	0.157	0.029	0.243
Bearing acoustic value after stabilization, G	0.036	0.017	0.121
Average particle size, μm	2.41	2.81	1.34

Table 6-2 Measurement results of acoustic characteristics of bearings (Test grease ②)

Symbol			A	B	C	D	E	F	G	H
Thickener	Isocyanate		MDI							
	Amine	ODA	○	–	–	–	○	–	○	–
		OTA	–	○	–	–	–	–	○	○
		CHA	–	–	○	–	○	○	–	–
		pTD	–	–	–	○	–	○	–	○
Base oil			PAO6							
Bearing acoustic value, G			0.028	0.084	0.154	0.238	0.025	0.098	0.022	0.168

Symbol			I	J	K	L	M	N	O
Thickener	Isocyanate		MDI						
	Amine	ODA	○	–	○	○	–	○	○
		OTA	–	–	–	–	–	–	○
		CHA	–	–	○	–	–	○	–
		pTD	–	○	–	–	○	–	–
Base oil			ADE			POE			
Bearing acoustic value, G			0.111	0.168	0.074	0.080	0.080	0.126	0.039

3. 2 Young’s Modulus

Table 7 and **Fig. 3** show the measurement results of Young’s modulus for thickeners. Preliminary measurements showed significant variation in measurement results using Method A, therefore the measurement was performed six times, with an average being taken on the four measurement results remaining after excluding the maximum and minimum Young’s modulus values. For Method B, the average of the results obtained after performing the measurement four times was used for comparison.

Comparing the different thickener compositions, the Young’s modulus for the thickener made from aliphatic amine-thickener was the smallest for both measurement methods, increasing in the case of alicyclic amine-thickener, then increasing further for aromatic amine-thickener. Comparing the two measurement methods, the measurement results obtained using Method A had greater variation than those obtained using Method B. This was believed to be due to the preparation conditions of the samples for Young’s modulus measurement, and in the case of Method A, the sample had been formed through compression, therefore residual stress was deemed an influencing factor. The sample prepared using Condition B was also formed through heat compression which, precisely speaking, did have an effect on the measurement values, however it was deemed this could be disregarded due to the applied compressive stress being small at only 0.06 to 0.21% of the obtained Young’s modulus.

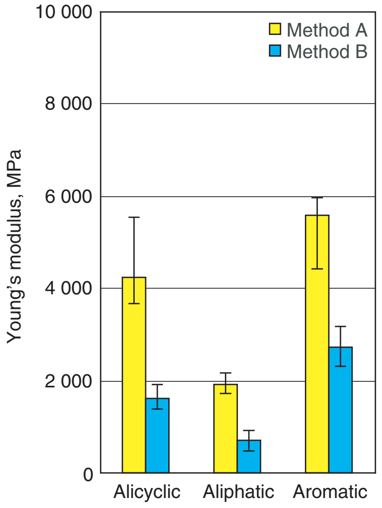

Fig. 3 Measurement results of Young's modulus of thickeners

Table 7 Measurement results of Young's modulus of thickeners

	No. of measurements performed	Method A	Method B
Alicyclic	1	4 737	1 568
	2	4 683	1 678
	3	4 193	1 526
	4	3 366	1 663
	5	3 369	–
	6	6 463	–
	Average	4 246	1 609
Aliphatic	1	1 980	685
	2	1 835	729
	3	1 960	734
	4	1 887	685
	5	1 739	–
	6	1 973	–
	Average	7 655	708
Aromatic	1	4 799	3 382
	2	4 842	2 621
	3	8 252	2 592
	4	5 056	2 273
	5	5 865	–
	6	6 641	–
	Average	5 601	2 717

3. 3 Aggregate State

3. 3. 1 Micrometer Scale

Table 8 shows the number of aggregate particles 1 μm or larger obtained through thresholding measurement images taken with a polarization microscope.

For the grease using non-polar PAO as the base oil, differences were observed between the aliphatic grease and other types of grease, with the aggregate density being less in the aliphatic grease. By using amines in combination, the aggregate density was less than if the amines were used in isolation.

For the grease that used polar ADE and POE as the base oils, the trend differed for the amine when used in isolation to that of combination use. When a single amine was used in the polar base oil, the aggregate density was significantly reduced. Meanwhile, if amines were used in combination, the result was 100 to 300 and base oil polarity was not recognized as having an effect.

3. 3. 2 Nanometer Scale

The aggregate state at a nanometer scale level was evaluated by radius of gyration and fractal index obtained through SAXS. **Figure 4** shows the measurement results. The information obtained through SAXS was fitted into the unified model shown in Equation (1) to obtain radius

Table 8 Measurement results of aggregate density of thickeners

Symbol			A	B	C	D	E	F	G	H
Thickener	Isocyanate		MDI							
	Amine	ODA	○	–	–	–	○	–	○	–
		OTA	–	○	–	–	–	–	○	○
		CHA	–	–	○	–	○	○	–	–
		pTD	–	–	–	○	–	○	–	○
Base oil			PAO6							
No. of aggregate particles 1 µm or larger within 1 field of view, no.			532	502	1 089	940	260	840	121	682
Symbol			I	J	K	L	M	N	O	
Thickener	Isocyanate		MDI							
	Amine	ODA	○	–	○	○	–	○	○	
		OTA	–	–	–	–	–	–	○	
		CHA	–	–	○	–	–	○	–	
		pTD	–	○	–	–	○	–	–	
Base oil			ADE			POE				
No. of aggregate particles 1 µm or larger within 1 field of view, no.			138	576	288	139	292	243	119	

of gyration (R_g) and fractal index (P). The radius of gyration expresses the size of the thickener, while the fractal index of the thickener fiber size is a characteristic value dependent on particle density, and in regards to thickener aggregate particles, expresses the state of base oil swelling. **Table 9** shows the R_g and P found in the measurement performed for this study.

For the grease using non-polar PAO as the base oil, in the case of a single amine it was observed that the radius of gyration/thickener fiber size were small when alicyclic amine was used and the effect of amine composition on the fractal index was slight, with the swelling of the base oil being the same. There was a trend demonstrating that both radius of gyration and fractal index were smaller in the case of mixed amines being used compared with when a single amine was used. This result shows that, by using mixed amines, it is possible to make thickener fiber size smaller and cause the base oil to swell within fibers.

For the grease that used polar ADE and POE as the base oils, while radius of gyration and fractal index do differ depending on the base oil composition and amine combination, the evaluation conducted this time did not clarify if grease composition had any effect on these indicators.

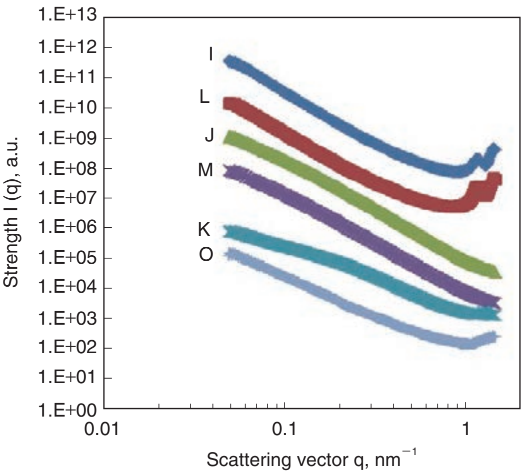

Fig. 4 Measurement results of SAXS

4. Considerations

4. 1 Effects of the Mechanical Properties of the Thickener on Acoustic Value of Bearings

The effect of thickener mechanical properties on bearing acoustic value was considered with regards to the Young's modulus. **Figure 5** shows the effect of such properties on bearing acoustic value relevant to test grease ①. The effect of Young's modulus was evaluated using three types of test grease ① where the average particle size was around the same level (between 1.3 and 2.8 µm).

Table 9 Investigation results of aggregatestate via SAXS

Symbol			A	B	C	D	E	F	G	H
Thickener	Isocyanate		MDI							
	Amine	ODA	○	–	–	–	○	–	○	–
		OTA	–	○	–	–	–	–	○	○
		CHA	–	–	○	–	○	○	–	–
		pTD	–	–	–	○	–	○	–	○
Base oil			PAO6							
Radius of gyration Rg, nm			53	52	35	46	26	37	44	44
Fractal index P			3.8	3.5	3.5	3.5	2.7	3.1	2.3	3.1

Symbol			I	J	K	L	M	N	O
Thickener	Isocyanate		MDI						
	Amine	ODA	○	–	○	○	–	○	○
		OTA	–	–	–	–	–	–	○
		CHA	–	–	○	–	–	○	–
		pTD	–	○	–	–	○	–	–
Base oil			ADE			POE			
Radius of gyration Rg, nm			39	34	26	38	37	(32)*	35
Fractal index P			3.3	3.5	2.5	3.1	3.4	(2.5)*	2.6

* : A periodic structure was observed in the SAXS spectrum therefore the value was used as reference but excluded from analysis

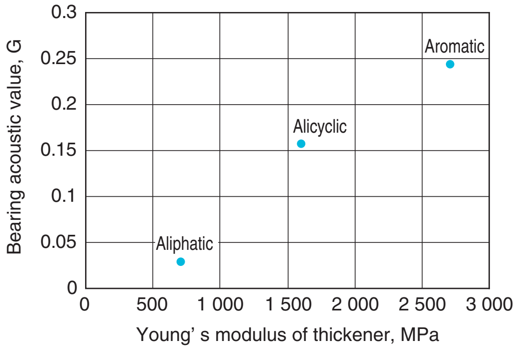

Fig. 5 Effects of mechanical properties of thickeners on acoustic characteristics of bearings

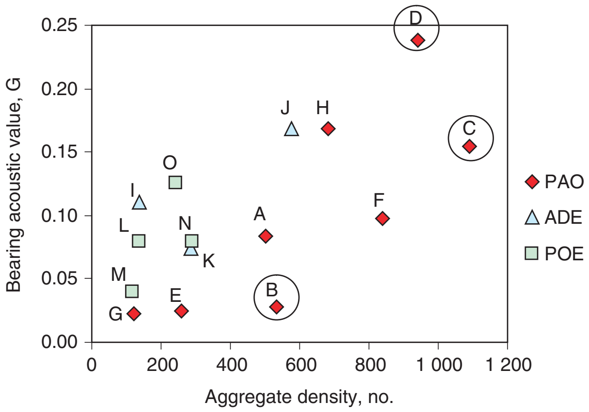

Fig. 6 Effects of aggregate density of thickeners on acoustic characteristics of bearings

In regards to the correlation between bearing acoustic value and Young's modulus, the bearing acoustic value would decrease in proportion with a decrease in Young's modulus. This is surmised to mean that an increase in bearing acoustic value is suppressed due to the fluctuation in oil film thickness when thickener particles penetrate the contact face between the rolling element and raceway being mitigated by the thickener becoming deformed.

4. 2 Effects of the Aggregate Density of Thickeners on Acoustic Value of Bearings

It is believed that both the size and density of thickener particles have an effect on the penetration of thickener particles to the contact face between the rolling element and raceway of roller bearings. The researchers believed that bearing acoustic value is effected by aggregated particles rather than primary particles, therefore investigated the number of aggregate particles 1 μm or larger and considered the effect of aggregate density of thickener on bearing acoustic value.

Figure 6 shows the effects of aggregate density of thickeners on the acoustic value of bearings. In cases where non-polar PAO were used as the base oils, a trend emerged whereby the acoustic value was greater when aggregate density was higher, and it was also observed that the frequency of aggregate particles becoming caught in the bearing had an effect on acoustic value. The data in **Fig. 6** allocated with symbols corresponds with test grease ① and test grease D has a high acoustic value. This is believed to be due to test grease D having a thickener with a high number of aggregate particles 1 μm or larger (high aggregate density) and small average particle size, therefore making it prone to becoming caught in the bearing. Test grease D is also believed to have a high acoustic value due to the high Young's modulus resulting in poor damping performance of membrane fluctuation by thickener deformation. In this study, the researchers were unable to clarify the extent to which these factors effected or contributed to acoustic value.

Even in cases where polar ADE and POE were used as the base oils, a trend emerged demonstrating that bearing acoustic value increases as the aggregate density becomes higher and aggregate density had a greater effect on bearing acoustic value than when PAO was used as base oil.

The researchers studied the aspect of solubility parameter with the belief that the affinity between thickener and base oil was a dominating factor affecting the aggregate state of thickener. Hansen solubility parameter (HSP) was used as the solubility parameter, and the HSP value was estimated using an algorithm based on chemical structure created by Toyota Central R&D Labs (atomic group contribution method) and commercially-available software (HSPiP v4.1.03). The results are shown in **Fig. 7**. The HSP distance expresses the relative distance between the thickener and base oil, and the smaller the HSP distance, the closer the thickener and base oil are to each other. In other words, the affinity between thickener and base oil is greater, which translates to less aggregation of the thickener. **Figure 7** shows a correlation exists between the HSP value and aggregate density for each base oil composition and this result suggests that aggregate density can be estimated by calculating HSP value, which in turn means that prediction of the bearing acoustic value would be possible. **Figure 8** shows the correlation between HSP value and bearing acoustic value. While it is possible to predict acoustic value from the HSP value due to their correlation in the case of grease which use PAO and ADE as base oil, no such correlation was observed in the grease that used POE as base oil. From these results, the researchers have predicted that there are other factors apart from aggregate density and HSP value which effect bearing acoustic value.

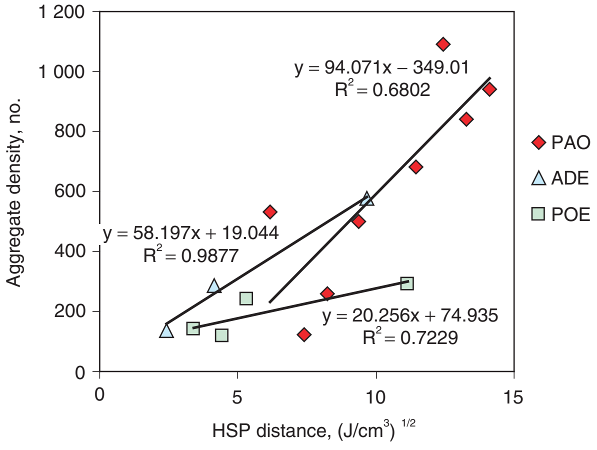

Fig. 7 Effect of compatibility between thickener and base oil on aggregate density of thickeners

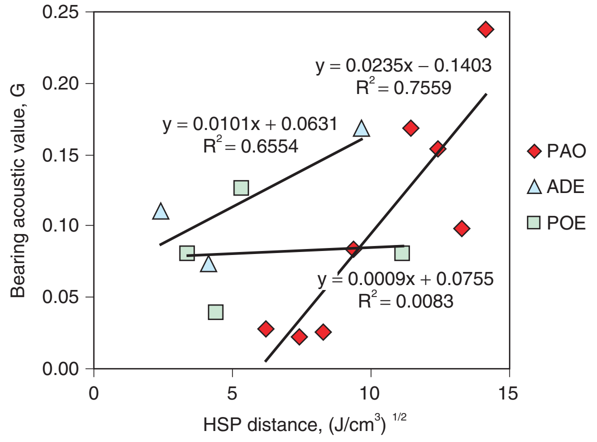

Fig. 8 Effect of HSP value on acoustic characteristics of bearings

4. 3 Effect of the Nanometer Scale Structure of Thickeners on Acoustic Value of Bearings

In recent years, improvements in analysis technology using synchrotron radiation has enabled analysis of thickener structure at a molecular crystal level, which was previously not possible. It is believed that the structure of thickener at a molecular crystal level also effects the bearing acoustic value therefore this study focused on the effect of thickener nanometer scale structure on bearing acoustic value. Using SAXS-based radius of gyration and fractal index as indicators of the structure of thickener at a molecular crystal level, the correlation with bearing acoustic value was investigated. **Figure 9** shows the results.

Thickener using POE base oil showed a high correlation between radius of gyration, which expresses thickener fiber size at a nanoscale level, and bearing acoustic value, however no correlation was observed in the case of thickener using ADE base oil. Meanwhile, regarding correlation between the fractal index, which indicates swelling due to thickener base oil, and bearing acoustic value, a trend emerged whereby the bearing acoustic value decreased as the fractal index decreased. In other words, it is assumed that the greater the thickener swells due to base oil, the softer the thickener particles become, hence reducing bearing acoustic value.

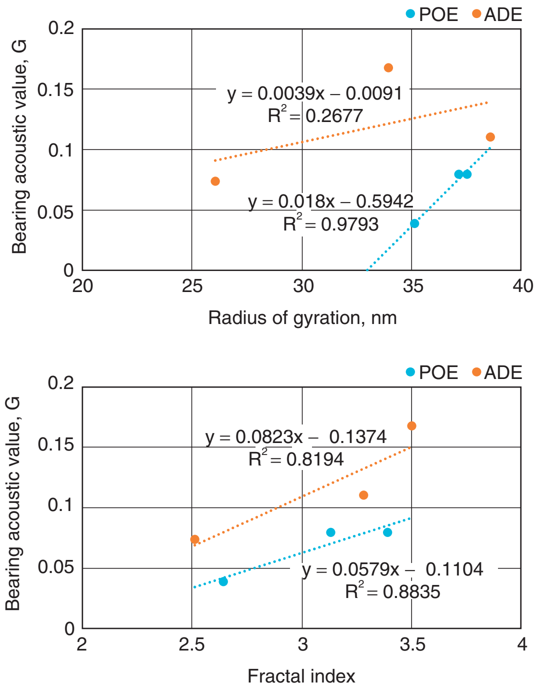

Fig. 9 Effect of nanometerscale structure of thickeners on acoustic characteristics of bearings

5. Conclusion

As a result of investigating the effects of thickener mechanical properties and aggregate state on bearing acoustic value, the following findings were made.

1) The mechanical properties and aggregate state of thickener has an effect on the bearing acoustic value. Suppressing penetration of aggregated thickener to the contact portions of bearings and reducing the elastic modulus of thickener is effective in reducing bearing acoustic value.
2) The aggregate state of thickener is effected by HSP distance at the micrometer scale level and fractal index obtained through SAXS at the nanometer scale level. The HSP distance is an indicator of base oil/thickener affinity, while fractal index is an indicator of the swelling state of thickener due to base oil and this study showed that bearing acoustic value could be reduced by keeping these two indicators minimal.

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