

## **Paper E**

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# **Analysis of Grease Lubrication of Rolling Bearings Using Acoustic Emission Measurement**

Juha Miettinen<sup>1</sup>, Peter Andersson<sup>2</sup> and Victoria Wikström<sup>3</sup>

<sup>1</sup>Tampere University of Technology, Machine Dynamics Lab, Tampere, Finland

<sup>2</sup>VTT Manufacturing Technology, Espoo, Finland

<sup>3</sup>SKF Engineering & Research Centre B.V., Nieuwegein, The Netherlands

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## **Abstract**

The behaviour of grease lubrication in a rolling bearing is less known than that of oil in the same type of tribological system. In recent years the research of grease lubrication has brought up several features of the grease lubrication that differ from the classical EHL theory of oil lubrication, notably that starvation is more prominent under grease lubricated conditions.

The goal of the present investigation was to clarify, by using a real bearing installation and realistic running conditions, how the fundamental properties of the lubricating grease influence the lubrication in a rolling bearing. The fundamental properties of the greases considered in the study were thickener concentration, base oil viscosity, base oil bleeding rate and consistency. Results obtained with grease lubrication were verified with pure oil lubrication.

The analysis of grease lubrication in the present investigation is based on the relative differences in the pulse count rate of the acoustic emission (AE) generated by the running of the bearing. In order to make the right decisions in condition monitoring of a bearing, the fundamentals of the behaviour of grease lubrication in rolling bearings and its influence on the AE signal have to be known. Moreover, AE has proven to be a good tool to study grease lubrication in-situ in a bearing. The results show that starvation of the lubrication situation increases with increasing thickener content, and decreases with lowered base oil viscosity. This is in agreement with film thickness measurements made in ball-and-disc type equipment.

## **1. Introduction**

Greases are the most common lubricants for rolling bearings. Typical applications of grease lubricated rolling bearings in industry we can find, for example, in centrifugal pumps. Grease lubrication is often used in slowly rotating sliding bearings, in oscillating guides and in gears of low rotational speed. Grease lubrication can be applied by using a centralised lubricating system for continuous grease supply into the bearing. Alternatively, sealed bearings filled with grease at the bearing factory or bearings re-lubricated at regular intervals are used.

When an oil is used for lubricating a rolling bearing, the lubrication situation under advantageous running conditions can be fully flooded and the contact surfaces are separated. In grease lubrication, the situation is different from the oil lubrication situation. Lubricating greases contain 5 - 30 percent of thickener, 70 - 95 percent of base oil, and additives like antioxidants, rust inhibitors, EP-additives and anti-wear additives. The base oil is bound to the thickener and cannot flow in the bearing as freely as a lubricating oil would. It is common assumption, that in grease lubricated rolling bearings, fully flooded conditions can occur in a freshly lubricated bearing but after a short time in operation the bearing is normally running under starved lubrication conditions. This study, applying acoustic emission to assess film thickness over time, was made to verify the assumption of starvation in-situ in an operating rolling bearing, and also to study the possibility of base oil replenishment in a bearing.

## 2. Grease lubrication fundamentals

Specific mechanisms are dominating the formation of the lubricating film in a rolling bearing. Cann [1], Baker [2] and Scarlett [3] quote three mechanisms for the formation of a lubricating film and for the replenishment of the lubricant into the inlet of the contact zone in a grease lubricated rolling bearing: (1) the separating film consists of both thickener and base oil components [1], (2) the grease acts as a reservoir to provide a controlled supply of oil which bleeds in to the contact zone [2] and (3) the separation of the rolling elements and the raceways is due to a thin layer of highly worked grease deposited in the rolling track during the first few hours of running [3].

Cann and Lubrecht [4] have divided the re-supply of the grease into the rolling contact into the continuous replenishment mechanism and the intermittent replenishment mechanism. The continuous replenishment mechanism consists of the replenishment of the bulk grease in the rolling track and of the local re-flow of base oil from the grease reservoirs around the track. Which mechanisms will be the dominating depends on the type of grease, the load and the design of the bearing. The efficiency of the replenishment mainly depends on the operational conditions of the bearing. It has been observed that in angular contact and thrust ball bearings, the spin motion of the balls is responsible for transporting the bulk grease into the rolling track, as shown by Åström, Östensen and Höglund [5] and Zhu and Neng [6]. A strongly different situation occurs, for example, in the cylindrical roller bearing in which the bulk flow of grease is minimal. Cann and Lubrecht [4] emphasises that intermittent re-supply of the grease can consist of several mechanisms, which make the grease "flow" in the bearing, and the vibration of the bearing is one of the most important factors for moving the grease in the bearing.

### 2.1. *The film thickness in grease lubrication*

Cann and Spikes [7] have investigated the formation of the lubrication film in a grease lubricated rolling contact, by measurements using an EHL ball on disc apparatus. They have found that the film thickness at constant rolling speed behaves according to the principle shown in Fig. 1. The film thickness changes with time; when the bearing starts to run after the addition of new grease the running situation is fully flooded. The film

thickness is built up by the base oil and the thickener of the grease. When the running of the bearing continues, the grease is rapidly pushed to either side of the raceway, thus causing a starved lubrication situation in the contact. In the fully flooded lubrication situation the film thickness is larger than the film thickness in oil lubrication using the base oil of the grease. Jacobson [8] has stated that the film thickness in fully starved conditions is approximately 40 nm, although the film thickness varies strongly with different greases and operation conditions.

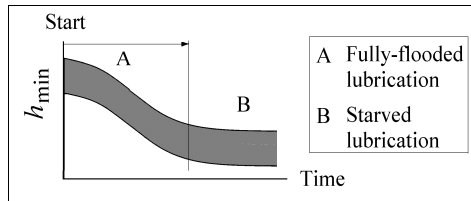


Fig. 1. Schematic illustration of the change in the film thickness in a grease lubricated rolling contact with time.

Cann [9] has studied in depth the influence of the properties of greases on the film thickness in starved grease lubricated rolling contacts, by measurements using a rolling contact EHL ball on disc apparatus. Cann has concluded that, in a starved grease lubrication situation, the degree of starvation increases with increasing base oil viscosity, grease thickener concentration and rolling speed. Correspondingly, the starvation decreases with increasing temperature. A higher thickener concentration reduces the bleeding of the base oil from the grease, hence the rolling contact becomes more starved. Cann [9] states that at real rolling bearing speeds the film thickness may drop to a fraction of the fully flooded thickness.

Palacois *et al.* [10] have studied the formation of the film thickness by measurements in grease lubricated point and line contacts. They have measured that the film thickness in line contact decreased during the test time, which was two hours. The authors explain that the drop in the film thickness was due to the rise in running temperature from 20 °C to 35 °C during the measurement. An additional explanation may be the bleeding of the base oil from the grease, or mechanical degradation of bulk grease, also causing increased oil bleeding. The test was repeated four times, in order to allow the temperature to sink back to 20 °C between the measurements. During the stop time of the measurements the base oil had time to bleed into the contact zone. When a new test was started, the film thickness was higher, but decreased during the test due to the starvation of the rolling contact.

Jonkisz and Krzeminski-Freda [11], and Aihara and Dowson [12], have presented measurement results for grease film thickness in line contacts. Jonkisz and Krzeminski-Freda state that in fully flooded conditions the grease film is about 1.5 times the oil film thickness obtained with the base oil of the grease. Aihara and Dowson [12] have concluded that the film thickness in grease lubrication at starved conditions is about 0.7 times the corresponding oil film thickness. However, according to Åström *et al.* [13] the film thickness in starved grease lubrication is 0.35-0.45 times the base oil film thickness. As a rough estimate, it can be assumed that the real value for the lubricating

film thickness under starved conditions is between 35 % and 70 % of the film thickness obtained with an oil of the same type as the base oil of the grease.

Dyson and Wilson [14] have studied the formation of the lubricating film in a grease lubricated line contact, with a two-disk device. Their observations are in agreement with the principle shown in Fig. 1. Additionally, the authors carried out repeated shut-down tests with a load of 9.8 kN and a rotational speed of 1600 rpm at a temperature of 60 °C. In the tests, the rotation of the test rig was stopped and immediately started again for a time of 15 minutes and then again stopped. The authors found out that in the beginning of every running period, the film thickness was high but decreased during the running period. With a grease having a lower base oil viscosity the film thickness was higher, but the film thickness decreasing effect was stronger. The authors do not give an explanation for this rheological behaviour. One explanation for this kind of behaviour may be found in the better flow properties of the base oil of lower viscosity, which supports oil flow into the contact zone. Another reason may be the higher bleeding rate of a thinner base oil from the grease.

It should be noted that all of the above mentioned work on film thickness was made in test rigs, for which the relation to operating conditions in rolling bearings is unknown.

## 2.2. *Acoustic emission in monitoring grease lubrication*

The acoustic emission (AE) can be described as a shock wave inside a material under stress. The shock, or transient elastic wave, which is generated by the rapid release of energy from a local source [15], radiates in spherical wavefronts and causes surface waves, *e.g.* Rayleigh waves, on the surface of the material. These waves can be measured with a sensitive sensor from the surface of the material. In the case of rolling element bearings, the acoustic emission is generated when the moving surfaces of the rolling elements, raceways and cages are contacting each other. In these contacts the peaks of the surface roughness and particles in the lubricant act as point sources of the acoustic emission. The acoustic emission indicates the lubrication conditions of the bearing according to the film thickness, the cleanliness of the lubricant and the smoothness of the mating surfaces. If the lubrication situation is good, in terms of a sufficient film thickness, the AE is low. In starved lubrication situations the film thickness is significantly thinner than in the fully flooded situation. Due to the small film thickness, a considerable number of asperity contacts occur between the surfaces, and a high AE level is generated.

There are several factors, *e.g.* the bearing load, rotational speed, temperature and cleanliness of the lubricating grease, which influence on the acoustic emission in grease lubricated rolling bearings. Therefore, the running conditions have to be taken into account, in order to make the right conclusions from the AE measurement results. The influence of these factors is presented in the references [16] and [17]. The frequency bandwidth in acoustic emission measurements is in the range 100 kHz to 1 GHz. The AE signal is typically analysed by counting the pulses that exceed a defined voltage level, which method is called pulse count method, or by measuring the RMS value of the acoustic emission. In the references [18,19] the acoustic emission measurement techniques and the analysis of the AE signal are described.

### 3. Experiments

The grease parameters, which influence on the lubrication situation was investigated were, thickener concentration, base oil viscosity, base oil bleeding rate and consistency of the grease.

#### 3.1. Equipment

The test rig used in the measurements is shown in Fig. 2a. In all the measurements the test bearing was a 6206 deep groove ball bearing; the bearing had an inner diameter of 30 mm, an outer diameter of 62 mm and a width of 16 mm, nine balls with a diameter of 9.52 mm and a pressed steel cage. The test bearing housing contained a singular ball bearing. For the preparation of grease batches with a reduced thickener concentration, a mixer at VTT was used. The mixer was capable of processing a 500 g batch of grease in a 600 ml glass beaker, by performing a combined rotating and vertically reciprocating motion of a mixing head in the glass beaker, see Fig. 2b.

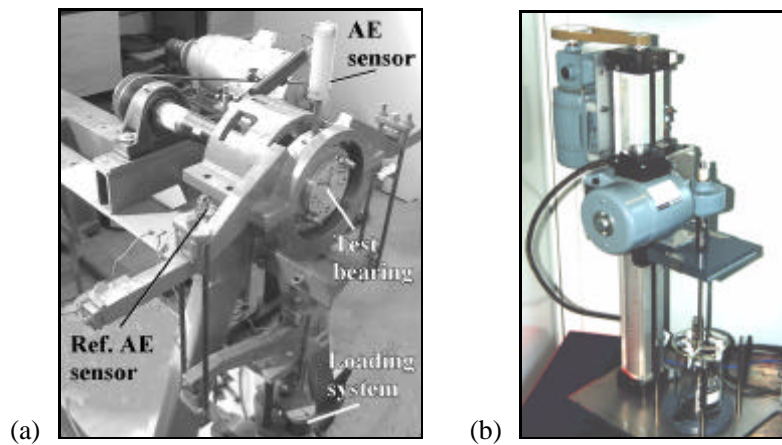


Fig. 2. (a) The test rig at TUT for grease lubricated rolling bearings and (b) the VTT grease mixer used in the present work.

During the AE measurements, great care was taken to minimise the effect of disturbances from the environment on the measurements. For that reason, the test bearing was separated from the loading system and from the support bearings by rubber and plastic vibration absorbers. In order to avoid an influence of the mounting of the bearing assembly, the greases were added into the bearing by pressing the grease through the bearing without removing the bearing from its housing.

#### 3.2. Experimental greases

The study was based on the nine greases shown in Table 1. Six of the greases (G1, G6-G10) were used as they had been received from grease manufacturers. The other three greases (G2-G4) were prepared from the grease G1 by dilution with oil.

The greases G2 and G3, which had a reduced thickener concentration, and the grease G4 which had a reduced base oil viscosity and a reduced thickener concentration, were prepared from the G1 lithium soap grease by dilution using the mixer shown in Fig. 2b. The greases G2 and G3, in which only the thickener content was reduced, were diluted by adding mineral oil, with additives, of the original base oil type into the grease. The grease G4, in which the base oil viscosity was reduced to 22 mm<sup>2</sup>/s and the thickener content to 5%, was diluted by adding mineral oil of 3 mm<sup>2</sup>/s viscosity and additives into the grease G1. All the addition of oil into the grease G1 was carried out under a simultaneously rotating and reciprocating mixing motion at slightly elevated temperature during 30 minutes.

The base oil bleeding rate measurements were carried out in accordance with the standard DIN 51817. In the test, the weight loss of the grease sample during 168 hours at 40 °C temperature is measured. The weight loss is the amount of the oil that has bled from the grease. The bleeding values (Table 1) of the greases G3 (41.2 %) and G4 (31.9 %) are rather high, when comparing these values to typical bleeding values of commercial greases, which are in the area from 2 to 6 %. The properties of the greases used in the tests are shown in Table 1.

Table 1. The properties of the greases in the tests. Values marked with \* are manufacturers data, while the other data consists of measured values.

Grease No.	Thickener	Thickener concentration (%)	Oil bleeding rate %/168 h @ 40 °C	Base oil viscosity mm <sup>2</sup> /s @ 40 °C	Base oil type	NLGI Grade / Penetration (mm/10 @ 25 °C)
G1	Lithium soap	8*	4.3	150	mineral oil	2* / 265
G2	Lithium soap	5	14.0	150	mineral oil	2 / 292
G3	Lithium soap	2.5	41.2	150	mineral oil	0 / 378
G4	Lithium soap	5	31.9	22	mineral oil	0 / 354
G6	Lithium complex soap	14*	3.0	460	polyalphaolefine	1.5* / 293
G7	Lithium complex soap	15*	2.4	100*	polyalphaolefine	2* / 235
G8	Tetraurea	7*	--	200*	mineral oil	1 / 326
G9	Tetraurea	14*	--	200*	mineral oil	2 / 284
G10	Diurea	7*	--	200*	mineral oil	3 / 244

### 3.3. Experimental procedure

In every measurement the bearing load was static and purely radial, and therefore no spin effect of the balls was present in the bearing. Depending on the type of measurement, the equivalent dynamic bearing load ( $P$ ), was 1/10 ( $C/P = 10$ ) or 1/30 ( $C/P = 30$ ) of the basic dynamic load rating ( $C$ ) of the bearing, which was 19500 N. The rotational speed was 400 rpm or 800 rpm, depending on the measurement. In every measurement, the rig was running for a sufficiently long time, typically one hour, for stabilising the bearing temperature before starting the measurements. The temperature was measured from the surface of the loaded side of the outer ring of the test bearing.

In the present measurement procedure, measurements with greases of the same kind were carried out using the same bearing installation, *i.e.* the bearing was not removed from the shaft or from the housing. This procedure was adopted for minimising the influence of the bearing assembly on the AE measurement results. In all tests the bearings were run-in by using grease G1, G6 or G8 depending on the grease types, which were under consideration. The different grease types in the individual test runs were pressed, by using a hand press, into the test bearing via grease nipples, which were located in the front plate of the bearing housing. During the addition of the grease the bearing was running. The added grease pushed the “old” grease out from the bearing. The amount of grease, that was pressed through the bearing corresponded to four times the free volume of the bearing and the housing.

In the AE measurements in the present investigation the pulse count method of the signal was used. The pulse count method is very suitable for a long measurement time, which in these measurements was typically from several minutes to a few hours. The pulse count data, which is stored during the measurement, only contains a fractional part of the total amount of the data from the original AE time signal. In all the measurements the equipment had the same settings, which were selected to make it possible to detect all the changes, from the minimum to maximum, in the acoustic emission.

#### **4. Results and discussion**

In the chapter 4 the results of the experiments are presented. The influence of the base oil bleeding rate was the most difficult effect to determine in the tests, hence its influence is discussed separately. In the end of the chapter, all the measurement results are summarised and scaled in order to minimise the influence of the running parameters or rotational speed, bearing load and running temperature and in order to help for making conclusions.

##### *4.1. Experiments with greases having different thickener concentration*

The influence of the thickener concentration in the grease on the AE pulse count rate is shown in Fig. 3. In the beginning of the test, the bearing was filled with the grease G1. When the grease G2 was added, the pulse count level dropped from 2300 to 1000 pulses/s. Finally when the bearing was filled with the grease G3, the level initially fell to a level of 600 pulses/s, but rose after about 10 minutes of running to a level of 1500 pulses/s.

With low thickener concentration the consistency of the grease became very low. Due to the low consistency of the grease G3, the rotation of the bearing threw the grease to both sides of the rolling track and only a minor proportion of the volume stayed in the contact zone. This observation was made when the front cover plate of the bearing housing was opened during the test.

The low thickener concentration of the grease seems to improve the lubrication situation, provided that the consistency of the grease is high enough to keep the grease in the vicinity of the rolling track. Considering the measurement results in Fig. 3, only with regard to the thickener concentration of the grease, the behaviour of the AE is of

the same kind as the behaviour of the film thickness in the measurements carried out with an EHL device by Cann [9], and Cann and Lubrecht [4]. From Fig. 3 it can be seen that the AE is increasing with increasing thickener concentration, which means increasing starvation of the lubrication situation. It must, however, be taken into account that the bleeding rate of the greases G2 and G3 are much higher than that of the grease G1. The higher AE level with grease G3 comparing to the level with grease G2 may be explained with the low consistency of the grease G3.

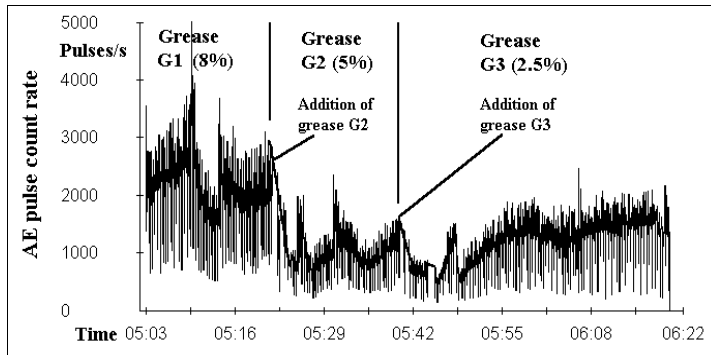


Fig. 3. The influence of the thickener concentration of the grease on the AE pulse count rate. Greases G1 (8 % thickener), G2 (5 % thickener) and G3 (2.5 % thickener). The rotational speed was 800 rpm, the  $C/P$  value 30 and the stabilised bearing temperature 32 - 35 °C.

#### 4.2. Experiments with greases having different base oil viscosity

The influence of the base oil viscosity on the AE pulse count rate is shown in the Figs. 4 and 5.

In the test presented by the Figure 4, the bearing was filled in the beginning of the test with the grease G2. When the grease G4 was added, the pulse count level fell from 1300 to 500 pulses/s, at which level it stayed until the test was stopped.

In the test represented by the Figure 5, the bearing was filled in the beginning of the test with the grease G6. Fig. 5 shows the influence of the addition of grease of the same type into the bearing (see "Addition of grease G6" in the figure). The addition of the grease reduced the AE level for temporarily, but the level soon rose back to almost the same level were it was before the re-greasing. When the grease G7 was added, the pulse count level fell from 28000 to 4000 pulses/s, at which level it stayed until the end of the test.

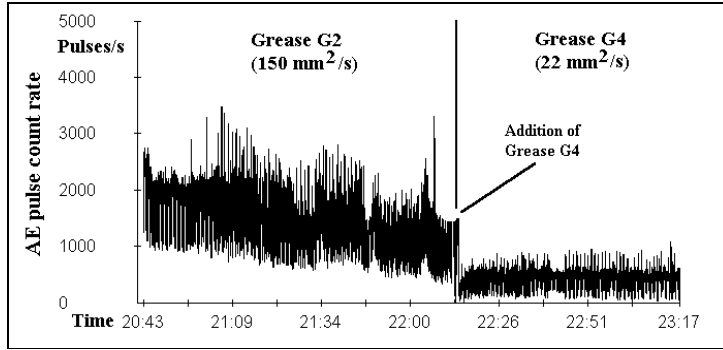


Fig. 4. The influence of the base oil viscosity of the grease on the AE pulse count rate. Greases G2 ( $150 \text{ mm}^2/\text{s}$ ) and G4 ( $22 \text{ mm}^2/\text{s}$ ). The rotational speed was 800 rpm, the  $C/P$  value 30 and the stabilised bearing temperature  $28 - 31 \text{ }^\circ\text{C}$ .

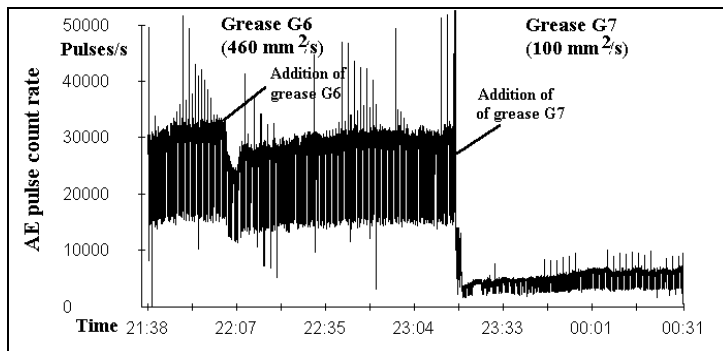


Fig. 5. The influence of the base oil viscosity of the grease on the AE pulse count rate. Greases G6 ( $460 \text{ mm}^2/\text{s}$ ) and G7 ( $100 \text{ mm}^2/\text{s}$ ). The grease G6 had a thickener concentration of 14 % and the grease G7 had a thicker concentration of 15 %. The rotational speed was 820 rpm, the  $C/P$  value 10 and the stabilised bearing temperature  $46 \pm 1 \text{ }^\circ\text{C}$ .

The AE measurement results with greases containing base oils of different viscosities show that the starvation of the lubrication situation is increasing with increasing base oil viscosity. The result is in agreement with the results of Cann [9], and Cann and Lubrecht [4], carried out with an EHL ball-on-disc device. The correlation between the AE measurement results and the bleeding properties of the greases is not significant. The results in Fig. 4 show that the AE level is lower with greases that have a higher bleeding rate. However, from the results in Fig. 5 we can conclude that the strongest factor for reducing the AE, or decreasing the starvation, is the base oil viscosity of the grease. The bleeding rate of the grease G6 is even higher and the thickener concentration is slightly lower than in the case of grease G7, while the AE is lower with the grease G7.

A base oil of lower viscosity enters more effectively into the inlet of the contact zone, makes the lubrication situation better and results in a lower level of the acoustic emission. If the base oil viscosity of the grease is lower the replenishment of the oil into

the contact zone is improved that decreases the starvation of the lubrication situation. Because the time available for the back flow of the base oil, after a preceding contact event, into the inlet of the contact zone depends on the time interval between two subsequent contact events, the replenishment depends on the rotational speed of the bearing and on the type of bearing. Chiu [20] has shown theoretically that replenishment is inversely proportional to base oil viscosity, but concluded that the time between passing rolling elements would under most circumstances be too short for replenishment to take place. Chiu's conclusion is however relying on surface tension and gravity as the forces driving replenishment, but as measurements of surface tension of base oil on a run-in surface were not available to Chiu, his conclusion should be revised. The measurement results, regarding the influence of the base oil viscosity of the greases, correlate with the measurement results presented by Miettinen [16], where the AE pulse count rate in measurements at elevated bearing temperature is reported.

#### 4.3. Experiments with greases of different composition

The results of the AE pulse count rate measurements with greases of different compositions, greases G1 and G6, can be found from Figs. 3 and 5. The AE pulse count level of the grease G6 is about 23 times higher than that of grease G1. The main factors responsible for the lower level of the AE with the grease G1 are the lower thickener concentration, the lower base oil viscosity and the higher bleeding rate of grease G1, all together producing a considerable lower AE pulse count rate. The results originate from different measurements, but the great difference in the AE levels of the greases G1 and G6 mainly reflects the difference in the properties of the lubricating greases and only to a minor degree the features of the different bearing installations. From the viewpoint of the base oil viscosity, the results of the measurement with the greases G1 and G6 are analogous with the measurement results for the greases G2 and G4, and the greases G6 and G7, see Fig. 4 and Fig. 5, respectively.

The results of the AE pulse count rate measurements with the greases G8, G9 and G10 are shown in Fig. 6. The results show that there is hardly any difference in the AE with the greases G8 and G9, although the concentration of the thickener of the grease G8 is only one-half of the concentration of the thickener of the grease G9. These results are different from the results obtained with the greases G1 and G2, where a lower thickener concentration produced a lower AE level.

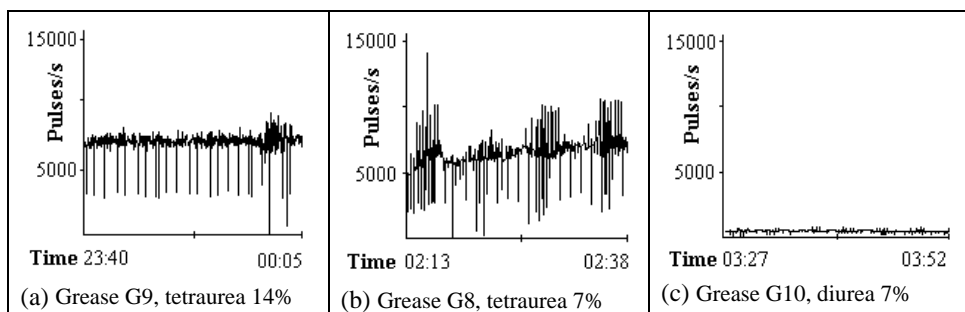


Fig. 6. The results of the AE measurements with the greases G8, G9 and G10. The rotational speed was 800 rpm, the  $C/P$  value 30 and the stabilised bearing temperature  $36 \pm 0.5$  °C.

The consistency of the greases G3 and G8 was very low. In the measurements, the greases G3 and G8 did not stay in the vicinity of the contact area but are pushed strongly to both sides of the rolling track. In this aspect, the greases G3 and G8 both behave in the same way. With the grease G10, however, the AE is only a fraction of the AE of the greases G8 and G9. The concentration of the thickener of the grease G10 is only 7%, but the grease G10 is much more consistent than the grease G8 probably due to the diurea thickener.

As all the present measurement results show, some level of acoustic emission always occurs when a bearing is running. In the case of clean greases, as in this investigation, the acoustic emission can be called the “acoustic emission noise level” of a clean grease. The “acoustic emission noise level” can be described as a sum of several factors. In addition to the factors that have been included in this investigation, there are other factors that influence on the generation of the acoustic emission in the case of clean greases. These factors can be *e.g.* the vibration level of the bearing, the viscous damping properties of the grease, solid particles of the grease thickener, insoluble ingredients from the manufacturing of the thickener, and solid additive particles.

According to work presented by Forster *et al.* [23], metal soap crystals dispersed in a hydrocarbon medium will form fibres in a three dimensional network held together by electrostatic forces. If the dispersion of the soap crystals is incomplete or inhomogeneous, solid crystals or soap fibre agglomerates may occur in the grease structure. Due to the history of a grease volume in a rolling bearing, due to age, working, oil bleeding and vibration, the soap fibre structure and concentration may be more or less different in the rolling contacts and in the bulk grease.

Studies by Eriksson *et al.* on the film formation in an EHL point contact lubricated with clean grease have shown that particles continuously pass through the contact, and that in pure rolling the particles or thickener lumps retain their size and shape during the contact, while in sliding-rolling contacts a partial shearing of the particles occurs [24]. Noise measurements at 50 Hz to 10 kHz on rolling bearings in an SKF Bearing Noise Tester, by Howard [25], have shown that clean greases give rise to more noise, *i.e.* vibrations, especially at higher frequencies, than a clean mineral oil used for reference.

The noise from oil lubricated bearings is a sum of noise from vibration due to ball and race irregularities, from contacts between the rolling elements and the races through the oil film, and from contacts between the cage and the rolling elements and races. The noise, in the present context, is mechanical vibration describing the smoothness in the running of the bearing. The mechanical vibration propagates in the structure of the machine and can cause, for example, resonance. The vibrating surfaces induce airborne vibration or noise. Similar phenomena influence on the level of the acoustic emission of the bearing. Subsequent work by Wunsch [26] supports the observations of a difference in bearing noise for oil and grease lubricated bearings and that this difference increases at higher frequencies. A comparison presented by Ward and Littlefield [27] has shown that different types of greases, when clean, give rise to noise of significantly different intensity, partly due to the different thickener types used in the greases.

#### 4.4. Experiments with oil lubrication

The behaviour of oil lubrication in rolling bearings has been examined in greater detail by other authors, and is better known than the behaviour of the grease lubrication. The measurements with pure oil lubrication in the present investigation were carried out in order to compare the results of the tests with oil lubrication with the results of tests with grease lubrication, and in order to acquire more confidence in the results of the measurements carried out under grease lubrication. A total of 7 different oils were studied in the bearing tests. All the measurements with pure oil lubrication were carried out in one test, hence the bearing installation was identical in all the measurements with oil lubrication. The addition of a specific oil was done in quantities of about 50 ml of oil in every five minutes. The measurement time with each test oil was 20 minutes. When the oil was changed into another, the new oil was added into the bearing three times during one minute in quantities of 100 ml of oil every time. The design of the bearing housing allowed excessive oil to flow out on the other side of the housing. All the oils, except the oil Oil7, were mineral oils. The oil Oil7 was a polyalphaolefine oil. The oil mixtures Oil2 - Oil5 were made by mixing the oils Oil1 and Oil6 together in different proportions.

The results of the AE measurements with oil lubrication are shown in Fig. 7 as a bar diagram. The AE values in Fig. 7 are average pulse count rates during the measurement time of 20 minutes, and values for the absolute viscosity and the calculated values of the kappa ( $k$ ) value are shown. The  $k$ -value is defined as the ratio of the actual viscosity ( $n$ ) to the viscosity ( $n_1$ ) required for adequate elastohydrodynamic lubrication [21], hence in bearing applications the  $k$ -value should be larger than 1, to obtain sufficient surface separation. The value of the actual viscosity  $n$  was determined at a temperature of 30 °C, which was the average temperature of the test bearing.

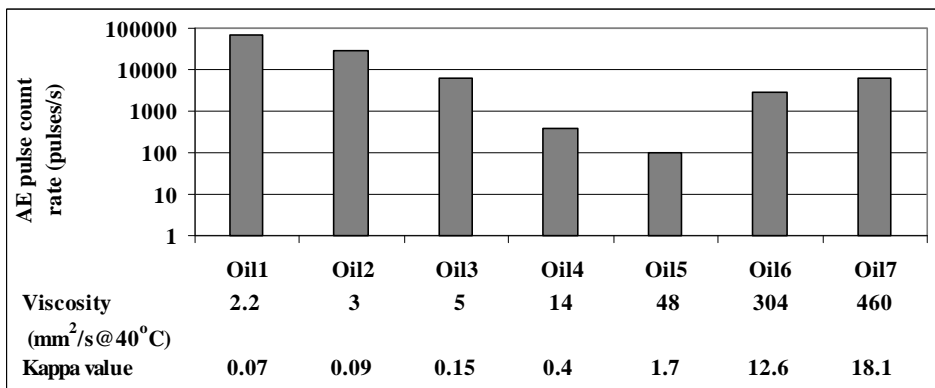


Fig. 7. The influence of the viscosity of the pure lubricating oil on the AE pulse count rate of the bearing. The kappa-values correspond the actual viscosities of the oils at temperature of 30 °C, which was the average bearing temperature in the test. The rotational speed was 400 rpm and the  $C/P$  value 10.

The best lubrication situation with test oils studied was achieved with Oil5. With lower oil viscosity the oil film thickness seems to become too thin to provide surface

separation, as indicated by a higher AE level. The  $k$ -values of Oil1 - Oil4 are lower than 1.0, which describes that the oil film thickness with these oils is insufficient for adequate elastohydrodynamic lubrication. With the oils of significantly higher viscosity, *i.e.* Oil6 and the Oil7, the AE level was higher. This result is not in agreement with the traditional EHL theory, according to which a higher viscosity produces a higher film thickness.

Chiu [20] has studied the lubricant replenishment and starvation in oil lubricated rolling contact by using a ball and disc device. Chiu has found that a high viscosity of the lubricant decreases the replenishment, and as a high speed reduces the time available for the reflow of oil back into the contact zone, the replenishment is further limited. The viscosity and time effects together produce a starved lubrication situation. Wikström and Jacobson [22] have measured the oil film breakthrough in spherical roller bearings. Their results show that the mean breakthrough time with a low-viscosity oil increased when the rotational speed increased, which means that the behaviour was in agreement with the traditional EHL theory. When the viscosity of the oil was high, the mean breakthrough time was decreased with increasing rotational speed, which means that the high viscosity and the high rotational speed caused starvation in the rolling contact.

The AE measurement results shown in Fig. 7 indicate the same kind of behaviour as the results of Chiu [20], and the results of Wikström and Jacobson [22]. The higher AE levels obtained with the oils Oil6 and Oil7 is a consequence of the starvation of the lubrication and is explained by the high viscosity of the lubricating oil and the high rotational speed of the shaft, as described above.

The measurement result with oil lubrication is analogous with the result of the measurements with the greases G2 and G4, shown in Fig. 4, and with the results for the greases G6 and G7, shown in Fig 5. In all the cases mentioned here, the higher viscosity of the oil limits the replenishment of the oil into the contact zone. This makes the lubrication situation more starved, as indicated by the rise in the AE level.

#### 4.5. Summary of the experiments

The results of the experiments of the present study are summarised in Table 2. In order to make the results more comparable the AE pulse count rate values of greases G6 and G7 are reduced to correspond the bearing load  $C/P$  value of 30. The reduction is based on measurement results with  $C/P$  value of 10 and 30 using the test bearing and the test grease G6. The ratio of the AE pulse count rate with  $C/P$  value of 10 to the AE pulse count rate with  $C/P$  was 3.9. The reduced AE pulse count rate value of the grease G6 is 7000 pulses/s (28000/3.9, see Fig .5.) and that of the grease G7 is 1000 pulses/s (4000/3.9, see Fig. 5.). The influence of the running temperature has been taken into account in the base oil viscosity by calculating the kappa value to correspond the running situation. The other data of the grease properties are from Table 1.

Table 2. The absolute and relative acoustic emission pulse count rate values of the test bearing lubricated with the different test greases. For greases G8 – G10 the oil bleeding rate values were not available. The AE values marked with <sup>1)</sup> are calculated values, see text. Kappa values are calculated to correspond the running temperature.

Grease No.	Thickener concentration (%)	Oil bleeding rate (%/168 h @ 40°C)	Kappa value at running temperature	Penetration (mm/10 @ 25°C)	Running temperature (°C)	Rotational speed (rpm)	Bearing load (C/P)	AE pulse count rate (pulses/s)	Relative AE rate
G1	8	4.3	10.6	265	32	800	30	2300	<b>1</b>
G2	5	14.0	10.6	292	32	800	30	1000	<b>0.4</b>
G3	2.5	41.2	10.6	378	32	800	30	1500	<b>0.7</b>
G4	5	31.9	1.6	354	30	800	30	500	<b>0.2</b>
G6	14	3.0	14.7	293	46	820	30	7000 <sup>1)</sup>	<b>3.0</b>
G7	15	2.4	3.0	235	46	820	30	1000 <sup>1)</sup>	<b>0.4</b>
G8	7	--	10.2	326	36	800	30	6000	<b>2.6</b>
G9	14	--	10.2	284	36	800	30	7000	<b>3.0</b>
G10	7	--	10.2	244	36	800	30	500	<b>0.2</b>

## Conclusions

The acoustic emission pulse count method was found to be a convenient method for monitoring the time dependent behaviour of the grease lubrication in real rolling bearing applications and realistic running conditions. The AE pulse count rate indicated the degree of the starvation of the lubrication situation.

The AE pulse count rate generated by the running of a grease lubricated rolling bearing in a stable running situation is a result of the combined effects of the grease parameters, thickener concentration, base oil bleeding rate, base oil viscosity or the kappa value and consistency or the penetration value of the grease.

The influence of the base oil viscosity on the formation of the lubrication situation was very clear. Low base oil viscosity decreases the starvation of the lubrication situation. This can be observed comparing the measurement results of greases G6 and G7, greases G1 and G7 and greases G2 and G4, although in the last case the grease G4 has remarkable higher bleeding rate than grease G2.

The influence of the base oil viscosity on the lubrication situation did not follow the traditional EHL theory for oil lubricated rolling bearings. This phenomenon was verified also with pure oil lubricated situation.

Low consistency, produced by a very low thickener concentration like in the case of grease G3 or by the composition of the grease like in the case of greases G6 and G8, causes the grease to drift away from the vicinity of the contact zone. This phenomenon increases the starvation of the lubrication situation.

The thickener concentration of the greases G6 and G9 was high, compared to the concentration of the grease G1. The high thickener concentration increases the starvation. In the case of the grease G7 the low kappa value eliminates the starvation effect of the high thickener concentration.

The influence of the bleeding rate on the starvation was difficult to separate from the influences of the other grease parameters. Although, comparing the greases G1 – G3 the AE pulse count rates are lower with higher bleeding rate values. In the case of grease G3 the bleeding rate is very high, but its improvement for the lubrication situation is diminished by the low consistency of the grease.

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