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Quantitative measurements of film thickness in a radially loaded deep-groove ball bearing

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ABSTRACT

The evaluation of the lubricant film thickness in machine elements working in elastohydrodynamic conditions is essential for the design aimed at improving their performance and durability. Among electrical methods for measuring the lubricant film thickness in these contacts the electrical capacitance is convenient to use because it relates directly to the film thickness by an inverse proportional relationship. Simultaneous measurements of optical film thickness and electrical capacitance have allowed the authors to perform quantitative evaluation of the film thickness in a model glass/steel contact, and develop a testing procedure which can be applied to steel/steel contacts. In the current paper a novel approach to film thickness measurements in rolling element bearings is presented. By replacing all but one steel ball with electrically insulating, ceramic balls evaluation of the lubricant film thickness in a radially loaded ball bearing has been achieved. The current procedure provides a valuable research tool for in-situ monitoring of lubrication condition, allowing studying the influence of operating parameters as well as the lubricant's chemistry.

1. Introduction

Electrical methods (electrical resistance, capacitance, inductance) have been widely used for the study of lubrication and lubricant film thickness measurements in model test devices as well as in machine components that work in elastohydrodynamic regime, such as rolling element bearings (Wilson [1], Leenders and Houpert [2], Magdun and Binder [3]), gears (MacConochie and Cameron [4]), cams (Vichard [5], Van Leeuwen et al. [6]), internal combustion engine piston ring (Hamilton and Moore [7], Sherrington and Smith [8]). When comparing the electrical methods, the advantage of electrical capacitance, over resistance, comes from the fact that according to the parallel-plate capacitor formula (Eq. (1)), the lubricant film thickness can be easily extracted if the capacitance of the contact is measured:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{h} \quad (1)$$

Here C is the capacitance between two parallel conducting plates of area, A, separated by a dielectric material with dielectric constant εr, and thickness h. Starting from the pioneering work on the lubrication of rollers by Crook [9], electrical capacitance has become the method of choice for the study of elastohydrodynamic (EHD) films between metallic surfaces. The disc machine, simulating a EHD contact between roller and raceway was also used by Dyson et al. [10] for the study of a wide range of fluids. Their work was then extended to grease lubrication few years later Dyson, Wilson [11]. The authors showed the comparison of film thickness measured with electrical capacitance for greases and their corresponding base oils.

Some of the first experiments involving electrical capacitance measurements on a rolling element bearing are due to Wilson [1]. He measured lubricant film thickness for a radially loaded double-row spherical roller and a single-row cylindrical roller bearing using the approach developed in earlier studies. Few years later Heemskerk et al. [12] presented the development of the “Lubcheck” apparatus designed for monitoring lubrication condition, based on electrical capacitance measurement. The bearing tested was a radially loaded deep-groove ball bearing lubricated with oil or grease. They were able to estimate the probability of asperity contacts, described in terms of metallic contact time fraction (PCT), and to measure the “lift-off” speed, defined as the speed at which the instrument recorded a PCT reading of 10%. The same instrument was then used by Leenders and Houpert [2], who measured the capacitance of radially loaded ball and spherical roller bearings lubricated with oil under the full-film and starved conditions, and then by Wikström and Jacobson [13] in their study concerning lubricant

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replenishment in spherical roller bearings. The "Lubcheck" instrument was also used to investigate the lubrication of bearings by refrigerant-lubricant mixtures Wardle et al. [14], Jacobson [15] and also to study the effect of surface micro-geometry on full film formation on a two-disc test rig Masen et al. [16].

Franke and Poll [17] presented a test rig in which, apart from the speed, temperature and friction torque the lubrication condition is also evaluated with the aid of the capacitance technique. In this work angular contact ball bearings were tested under pure axial load, lubricated with ten test greases. The same experimental setup and film thickness measurement approach was subsequently used by Gatzen et al. [18] and Wittek et al. [19] under grease lubrication.

One of the very limited comparative studies covering both, a model test device and full bearing tests, is due to Baly et al. [20], The authors show the measurements of grease film thickness with optical interferometry on ball-on-flat rig, and electrical capacitance for a rolling element bearing. Experimental setup and procedure for the bearing part is similar to that used by Franke and Poll [17].

The study of lubrication in ball-on-flat contact has certain advantages, however there are few factors that play an important role in the lubrication of rolling element bearings, which cannot be replicated in model ball-on-flat devices. Longer times between successive over-rollings, lubricant flow inside a full bearing, the level of starvation, the contact area geometry, and the dynamics of the rollers and cage, all influence lubricant film thickness and are close to impossible to replicate in a ball and disc model contact (Lugt [21]). Also, a significantly different time scale of such experiments, in comparison with the full bearing tests, as pointed out by Wikström and Jacobson [13], is another disadvantage of ball-on-flat devices.

Murer et al. [22] used electrical capacitance sensors to measure the load distribution in rolling bearings. They successfully compare the experimental results with finite element analysis. Schnabel and co-workers [23] argue that the behaviour of contact capacitance in mixed regime is not well known thus they carried out an investigation into the running – in of rolling bearings by measuring EHL contact impedance. They conclude that further research is needed in order to understand the role of additives in impedance measurement.

Thus, despite the importance of optical film thickness measurements on model ball-on-flat rigs, there will always be need for full bearing tests, as only those can provide a full understanding of the behaviour of lubricants in highly loaded, bearing contacts.

Relatively recently Jablonka et al. [24] performed quantitative film thickness measurements with electrical capacitance in a ball-on-flat experimental setup. By using a chromium-coated glass disc simultaneous measurements of the lubricant film thickness by optical interferometry and electrical capacitance have been performed. A procedure to extract film thickness from the measured capacitance was developed and then applied to a steel-on-steel EHD contact. In the following paper [25] this approach was used to investigate the influence of lubricant's polarity on capacitance measurements and showed a surprisingly different behaviour of polar fluids in comparison to nonpolar. The current study is the extension of the previous work on EHD rig to the radially loaded deep-groove ball bearing. In the bearing tested all but one steel ball are replaced with ceramic balls, making it possible to follow the capacitance variation as the steel ball travels a full cycle. It should be noted that film thickness measurements with electrical capacitance on a radially loaded bearing are much more complex than for the axial load case, used in Refs. [19,20]. For axially loaded bearings the load is equally shared by all rolling elements making the calculations much simpler. In the measurements of radially loaded bearings, the load distribution within the bearing must be considered.

2. Experimental setup

2.1. Ball-on-flat device

The first part of the experiments was carried out on a PCS Instruments EHD test rig. The rig has been modified in order to allow measurements of electrical capacitance between the disc and the ball. The disc and the ball are electrically insulated from each other and the rest of the rig and the capacitance is extracted from the impedance measured with a Solartron 1260 Impedance Analyser.

The measurements were performed at a frequency of 100 kHz and a signal voltage of 0.1 V was employed in most experiments. In the case of the mineral oil used it was necessary to modify testing (temperature) and impedance measurements (voltage) conditions in order to improve the quality of the data obtained. In the current settings the impedance is measured over 1 s and the average value of the capacitance is calculated and supplied directly by the instrument. For each speed 50 such readings are taken and the average value is used for the calculations. The experimental conditions are summarised in Table 1.

Two disc materials were used in this study. At first tests with a glass disc coated with chromium layer on the contacting surface were performed. This allowed simultaneous measurements of capacitance and film thickness with an optical interferometry method, as described in Ref. [24]. The chromium coated glass disc was then replaced with a steel disc and capacitance measurements have been carried out in similar working conditions of load and speed.

2.2. Rolling element bearing setup

The second part of the experimental work was performed in a bearing test rig. A 6306 ETN9 deep-groove ball bearing (DGBB) with a polymer cage and the inner and outer diameters of 30 and 72 mm was used. A radial load in the range between 1 and 6 kN was applied and the tests were performed over the range of entrainment speeds from 0.12 m/s up to 0.91 m/s (95–737 rpm). The Hertzian pressure, for the inner ring varied between 1.53 GPa and 2.64 GPa, while for the outer ring between 1.34 GPa and 2.27 GPa. The bearing was lubricated with a few drops of lubricating oil. In order to prevent starvation at high rolling speeds, small amount of oil was added before a sweep of speeds for each load. All tests were performed at room temperature and the bearing was run under self-induced temperature conditions. The temperature was measured on the outer ring before and after a sweep of speeds for each load.

In the bearing under study all but one steel ball were replaced with ceramic balls of the same radius (made of silicon nitride – Si_3N_4) and thus only the capacitance of the contact between the remaining steel ball and the raceways was measured. A "Lubcheck" capacitance voltage divider was used for the measurements. Details of this instrument and principle of operation can be found in Refs. [12,13,26]. The values were displayed and recorded with an oscilloscope. The schematic of the experimental setup can be seen in Fig. 1.

An example of the data displayed on the oscilloscope's screen is shown in Fig. 2.

Apart from the "Lubcheck" signal, the speed and load are recorded continuously, and also a pulse signal is registered when the steel ball passes the position of the maximum load at the bottom position of the bearing. This allows detecting any misalignment caused by improper bearing mounting, which could also lead to significant errors in film thickness calculation.

The procedure allows following the steel ball as it goes around a full rotation of the inner ring and recording very rapid variations of the signal measured. For each speed setting five measurements were taken, each consisting of three or four cycles, depending on the speed. The

Table 1
Testing conditions in ball-on-flat setup.

Lubricant	Glass disc (0.65 GPa)	Steel disc (1.04 GPa)
Mineral oil	40 N, 25 °C, 0.10 V, 0.01–0.23 m/s	40 N, 40 °C, 0.05 V, 0.03–0.31 m/s
PAO4	40 N, 25 °C, 0.10 V, 0.01–0.46 m/s	40 N, 25 °C, 0.10 V, 0.01–0.46 m/s