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CAPACITANCES AND LUBRICANT FILM THICKNESSES OF GREASE AND OIL LUBRICATED BEARINGS

Rolling Element Bearings II: Rolling Element Bearing Dynamics

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INTRODUCTION

The electrical capacitance of lubricated contacts and bearings is a parameter that has been investigated for many years [1–3].The focus of these investigations was to examine the film-thickness of the elastohydrodynamic contact between the rolling elements and the raceways. Nowadays the capacitance is not only of interest for the field of lubrication but also for a drive system behavior and the occurrence of bearing currents and electrical erosive wear. Modern drive systems can be characterized more and more by variable-speed operation that comes with many advantages like an increased efficiency but also some disadvantages. One of these is the occurrence of so called parasitic currents which are a result of the common-mode voltage U_{cm} that is inherent in the widely used voltage source inverters. The capacitance of drive system bearings – and other parts like gears [4, 5] – combined with motor inherent capacitances creates a capacitance voltage divider. As a result, a voltage U_{b} that is proportional to the common-mode voltage occurs at the motor bearings. Possible arc discharges in the lubricant gap can melt or vaporize material in the bearing raceways. This leads to a normally grey-frosted raceway with no influence on the bearing lifetime, or to so-called corrugated patterns (see Figure 1 a), which reduce the bearing lifetime. Furthermore, the discharges damage the lubricant due to the high temperature in the discharge arcs (see Figure 1 b). Unscheduled maintenance and therefore higher costs are the result. There are three main types of bearing currents. One of them is the so called EDM-current (Electrical Discharge Machining) which depends on the breakdown effects inside the lubrication gap of the rolling element bearing. In contrast to the two other types of bearing currents (circulating and rotor ground currents), the occurrence of EDM currents is strongly influenced by the common-mode voltage and the parasitic capacitance network behind the motor terminals which consists of the stator winding-to-frame capacitance C_{wf}, the stator winding-to-rotor capacitance C_{wr}, the rotor-to-frame capacitance C_{rf} and the capacitances C_{b} of the rolling bearings at the drive end and non drive end of the motor. Equation 1 gives the ratio between the common-mode-voltage and the bearing voltage – the so called Bearing Voltage Ratio BVR – depending on the capacitance network.

$$BVR = \frac{U_{\mathrm{b}}}{U_{\mathrm{CM}}} = \frac{C_{\mathrm{wr}}}{C_{\mathrm{wr}} + C_{\mathrm{rf}} + C_{\mathrm{b\,DE}} + C_{\mathrm{b\,NDE}}} \quad (1)$$

a) b)

Fig. 1: Fluting on a bearing raceway (a) and charred lubricant due to EDM-currents (b)

BASICS

A prediction of EDM-currents requires the knowledge of the bearing capacitances to calculcate the voltage across the bearing and the minimum film-thickness in a bearing to determine the critical breakdown voltage. Each EHL-contact can be described as a system of three parallel capacitances as shown in Figure 2. The capacitance of the Hertzian contact can be calculated quite well, however the inlet and outlet zone of the Hertzian contact also contribute to the total capacitance [2, 6]. The influence of these areas is often described by a constant factor (usually 3.5) while in reality the factor depends on geometry and film-thickness. For a better understanding measurements and calculations for a single contact on a two-disc-testrig and for a multi contact in a bearing are conducted in this work.

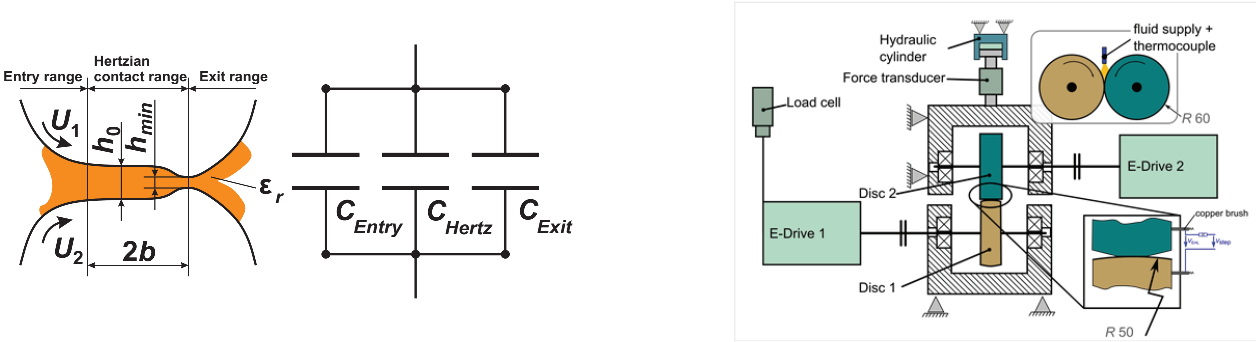

Fig. 2: Left: Equivalent model for capacitance in an EHL-Contact (according to [2, 3]); Right: Twin disc test rig used

With knowledge of the Hertzian contact area A_{Hertz}, the central film-thickness h_0 and the dielectric behavior of the lubricant ε_r, equation 2 can be used to determine the Hertzian capacitance C_{Hertz}. These parameters are all dependant on factors like the pressure p, temperature ϑ, contact force F_N, curvature radius R, combined Young's Modulus E', hydrodynamic speed v and viscosity η.

$$C_{\text{Hertz}} = \varepsilon_0 \cdot \varepsilon_r(p,\vartheta) \cdot \frac{A_{\text{Hertz}}(F_N,R,E')}{h_0(\bar{v},F_N,R,\eta(p,\vartheta))} \quad (2)$$

The total capacitance of a contact can be calculated by equation 3 if the capacitance of the entry and exit zone are known or if one assumed or calculated a value for $k_C = C_{\text{total}}/C_{\text{Hertz}}$.

$$C_{\text{total}} = C_{\text{Entry}} + C_{\text{Hertz}} + C_{\text{Exit}} = k_C \cdot C_{\text{Hertz}} \quad (3)$$

SINGLE CONTACT MODEL

To allow for a comparison of the single EHL contact capacitance model measurements were conducted using a twin disc test rig shown in Figure 2 right. Here, a single EHL contact is investigated. The contact is established between a cylindrical and a crowned disc which are pushed together with a defined normal force. The load, speed, oil temperature, and slide to roll ratio (*SRR*) can be variied. The use of insulating bearings and couplings, allows for a defined path only through the EHL contact. During the experiments the capacitance of the contact was measured using a measurement system which was applied to the shafts. The shafts were contacted using copper brushes. Subsequently a voltage step V_{step} was applied over a charing resistor R. The Voltage of the EHL contact V_{EHL} was measured. From the time constant of the V_{EHL} the capacitance of the EHL contact could be determined. As only one contact is present Equation 3 can be used to describe the total capacitance C_{total}. Furthermore, the Hertzian contact area and the film thickness can be acurately calculated thus allowing for the determinitaion of C_{Hertz}. Therefore, the factor k_c can be accurately determined and compared to theoretically expected value resulting from simulations of the capacitance of the contacting geometries.

BEARING AS MULTI CONTACT MODEL

Contrary to the single-contact model of the two-disc testrig, a bearing consists of multiple contacts with different capacitances. These capacitances can be combined to a single bearing capacitance. However, for this the cage design is important as it influences the way the contact capacitances are combined. For a bearing with a conducting cage and by assuming that there is no separating fluid film between the balls and the cage, the equivalent circuit is shown in Figure 3. All contacts at one ring are in parallel with each other and then in series with the other rings' capacitances. For a bearing with N rolling elements Equation 4 can be used to calculate the bearing capacitance C_b from the inner-ring capacitances C_i and the outer-ring capacitances C_o.

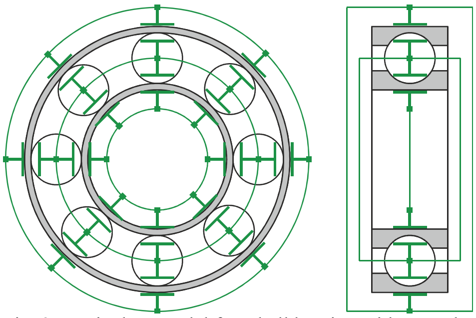

Fig. 3: Equivalent model for a ball bearing with a conducting cage

$$C_\mathrm{b} = \frac{\sum_{i=1}^{N} C_{i,\mathrm{i}} \cdot \sum_{i=1}^{N} C_{i,\mathrm{o}}}{\sum_{i=1}^{N} C_{i,\mathrm{i}} + \sum_{i=1}^{N} C_{i,\mathrm{o}}} \qquad (4)$$

A bearing test-rig as described in [7, 8] was used to measure the capacitance behavior of ball bearings 6008 for different operating conditions like temperature, speed, load and various lubricants using an oil bath as lubrication method. The measurements – examples are given in Figure 4 – show a few characteristic effects:

- increasing speed leads to lower capacitances due to the higher film-thickness
- increasing load leads to higher capacitances due to the bigger Hertzian contact area
- increasing temperature leads to higher capacitances due to the decrease in viscosity and therefore film-thickness
- at high speed and high viscosity (low temperature) the capacitance increases again due to starvation effects
- the influence of the Hertzian contact capacitance decreases with higher film-thickness

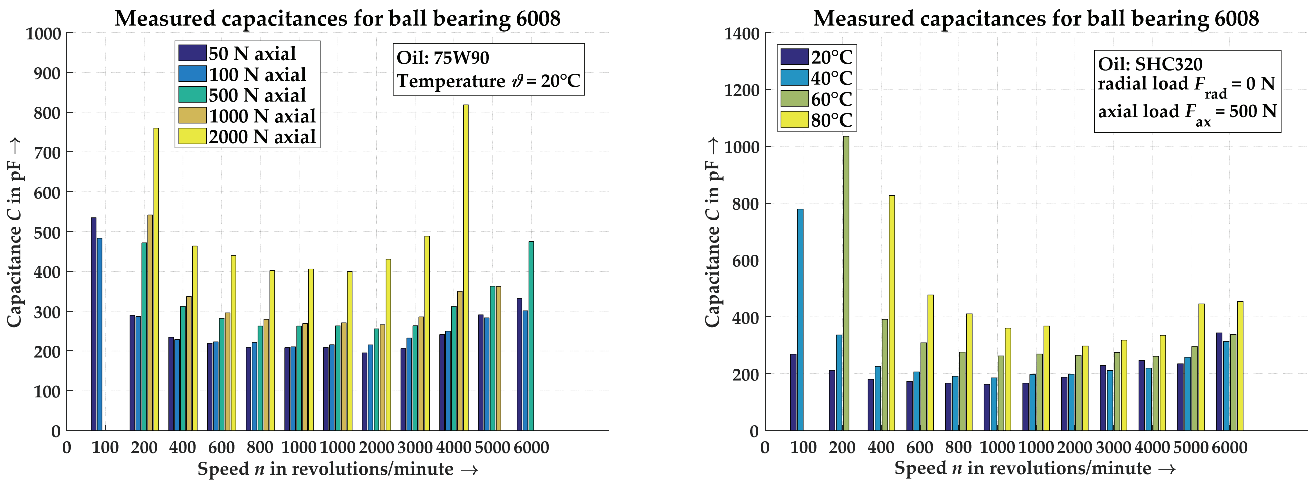

Fig. 4: Measured capacitances for ball bearing 6008 by various axial loads and speed (left diagram) and for different temperatures (right diagram)

To determine the effect of inlet and outlet zone of the EHD-contact the ratio between the calculated Hertzian capacitance and the measured capacitance is plotted over the calculated film-thickness (Figure 5 left). In this diagram different lubricants, viscosity and speeds were used. It can be seen that regardless of the parameters that create the film, a comparable behavior between measured and calculated capacitance exists. The resulting curve can be used to determine the total capacitance of a ball bearing (Figure 5 right) and is a confirmation to the results of Jablonka et. al. [6] and their tests with a ball on disc contact. Similar analysis for systems with axial load show comparable results but with reduced values for k_C as the Hertzian contact is larger due to the increased number of loaded balls. However, the often used value $k_\mathrm{C} = 3.5$ is part of this curve in an area with where many measuremts are performed.

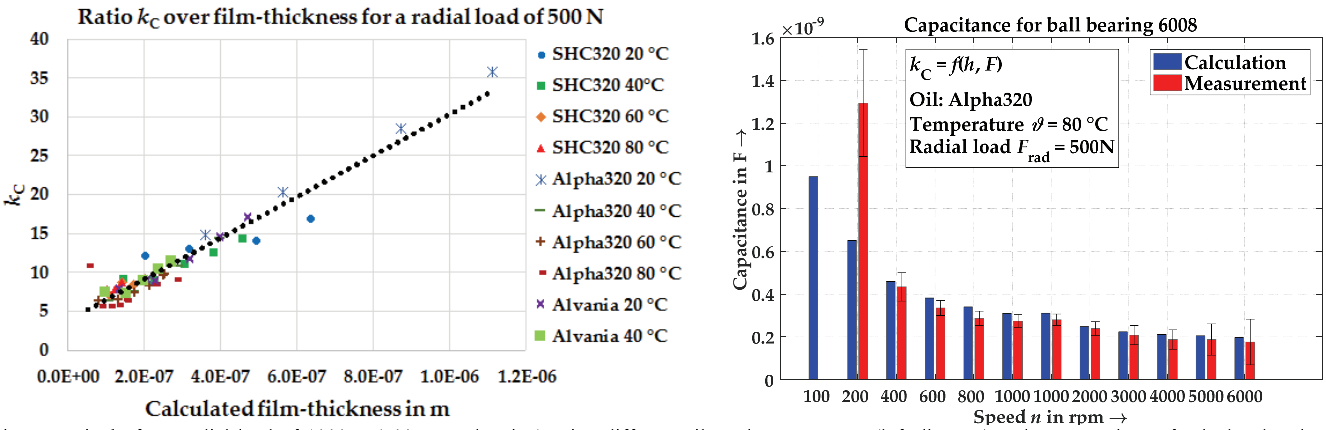

Fig. 5: Ratio k_C for a radial load of 1000 N (500 N per bearing) using different oils and temperatures (left diagram) and a comparison of calculated and measured capacitance for the same load condition (right diagram). SHC320: PAO oil ISO VG 320. Alpha320: Mineral oil ISO VG 320, Alvania: Grease base oil ISO VG 100

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KEYWORDS

EHL: EHL (General), Rolling Bearings: Rolling Element Bearings, General, Wear: Electrical Erosive Wear.