Comparison of analytic and numeric methods to calculate ball bearing capacitance

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ABSTRACT

The electrical characteristics of rolling bearings become increasingly important. This work examines various methods for calculating the capacitance and contributes to a deeper understanding of the electric behavior of the rolling bearing. The focus is on the peripheral zone outside the Hertzian area of loaded as well as unloaded rolling elements. Semi-analytical approximations and finite element simulations are applied and a closed-form analytical two-dimensional solution is derived for comparison. The rolling contact of radially loaded deep groove ball bearings serves as an application example. The results show that the semi-analytical approximations reproduce the trend from numerical and analytical calculations, but show significant quantitative differences. Particularly the contribution of unloaded rolling elements to the total capacitance has been underestimated so far.

1. Introduction

The electrical properties of rolling bearings are becoming increasingly important: On the one hand, with an increasing number of converter-fed electrical machines, electrically induced bearing damage is on the rise, making research in electrical bearing failures a “key bottleneck in electric vehicles at present and in the forthcoming decades” [1]. An improved electrical characterization of the bearings can help to better predict and prevent electrical bearing damages in electric machines [2]. Multiple studies have been carried out on this topic, introducing electric models of rolling bearings [3–8]. On the other hand, electrical bearing characteristics can be used sensorially, since they depend on the lubricant film thickness and thus on the load condition [9], which in turn requires a precise electrical modeling of the bearing. Therefore, electrical models have been improved and utilized for sensorial applications [10–12]. In addition, capacitance measurements are used for lubrication film investigations as they have certain advantages compared to tactile or optical measurements [13]. Different researchers have improved electrical models of rolling bearings to improve capacitive film thickness measurements [14–16].

The work at hand contributes to a better understanding of the electric behavior of rolling bearings by comparing commonly used semi-analytic formulae for the bearing capacitance with a newly derived analytic formula in 2D and a 3D finite element (FE) simulation. In addition, different implementations of the semi-analytic formula are compared and discussed.

1.1. Bearing capacitance fundamentals

This work studies radially loaded deep groove ball bearings in a fluid friction regime. Since lubricants used in bearing applications typically feature a high resistivity, the dominant electric characteristic for frequencies in and beyond the kHz regime becomes the permittivity \( \varepsilon \). Hence, the bearing’s capacitance and not its resistance is significant. Figure 1a shows an example of a capacitor network of a deep groove ball bearing with a conductive cage based on the model of Prashad [17]. Radially loaded bearings develop a load zone where rolling elements carry the load. Therefore, this work differentiates between loaded and unloaded rolling elements.

For the loaded rolling elements, Figure 1b, a Hertzian contact area \( A_{\text{Hertz}} \) with the central lubricant film thickness \( h_c \) is formed. Equation 1 allows an estimation of the capacitance of the Hertzian contact:

\[
C_{\text{Hertz}} = \frac{\varepsilon A_{\text{Hertz}}}{h_c}. \tag{1}
\]

Areas outside the Hertzian area and unloaded rolling elements also contribute to the total capacitance, Figure 1c, [12]. Therefore, the capacitance calculated in Equation 1 underestimates the result. This necessitates the introduction of a correction factor \( k_C \). Equation 2, which is multiplied with the capacitance of the Hertzian contact to produce a more precise result:

\[
C_k = \frac{\varepsilon A_{\text{Hertz}}}{h_c} k_C. \tag{2}
\]

The correction factor was estimated by Barz to \( k_C = 3.5 \) [18] and is used or reviewed in various literature [6, 19–23]. Realizing that a constant factor does not result in a satisfying precision, others worked towards a variable factor: Furtmann derived a film thickness dependent factor \( k_C(h_c) \) from experiments for a given bearing [19]. Schneider derived an empirical formula for \( k_C \) based on numerical simulations as a function of speed, material, load and contact.
ellipticity [24]. In contrast, the goal of this work is to substitute the correction factor by phenomenologically motivated formulae with an additional focus on unloaded areas as for loaded rolling elements outside the Hertzian area as well as unloaded rolling elements. Different authors, i.e. [11, 12, 17, 21, 24–26], used a semi-analytical method, Equation 3, to compute the capacitance of these areas as a function of a varying lubrication gap height \( h(x, y) \):

\[
C_{\text{semi}} = \int_A \frac{\varepsilon}{h(x, y)} \, dx \, dy. \tag{3}
\]

Thereby, the capacitor area \( A \) is decomposed in infinitesimal area elements \( dA \) that are typically expressed in Cartesian coordinates as \( dA = dx \, dy \). The area \( A \) is the area of the sphere projected in the contact direction and is \( A = \pi r_{re}^2 \) large with the radius of the rolling element \( r_{re} \).

For the application case of rolling bearings, the question how much error is introduced by the approximations is investigated in-depth for the first case in this work. For this purpose, different calculation models are implemented in addition to the approximate methods, i.e., a two-dimensional analytical model as well as a two- and a three-dimensional finite element (FE) model. These are compared with each other and the deviations of the calculated capacitances are quantified.

The following assumptions were made to develop these models: The electric permittivity \( \varepsilon \) is constant for a given temperature and pressure and is independent of the electric field strength resulting in a non-coupled and linear problem. The ball-raceway contact is assumed to be completely surrounded by oil. Approaches to account for the oil distribution around the contact can be found in [21, 24]. Furthermore, the contact surfaces are assumed to be ideally smooth as is usually the case in literature [5, 12, 17, 21, 24, 26]. Insights on rough rolling surfaces are given in [6, 10].

2. Theory and Calculation

2.1. Dimensionless bearing geometry for 2D calculation

For the two-dimensional (2D) calculations, the geometry is expressed by non-dimensional quantities. This is achieved by dividing all geometry parameters by the rolling element’s radius \( r_{re} \). For easier recognition, all dimensionless parameters are noted in Greek letters, cf. Table 1. The minimal distance between race and rolling diameter \( s \) is described by the dimensionless quantity \( \alpha = s/r_{re} \), \( \beta = b_i/r_{re} \) expresses the groove width, and \( \tau \) the groove radius. Depending on the section plane, it is derived either from the race conformity \( f \), which in return is the ratio between groove radius and ball diameter, or the race radius \( r_i \) in the other section plane respectively. \( \sigma \) is the distance between race and ball center and is calculated from the quantities above as shown in Table 1, which shows the orientation of the dimensionless coordinate system \((\xi, \eta, \zeta)\) as well. In a polar coordinate system, \( \phi = r/r_{re} \) describes the dimensionless radial coordinate. Furthermore, two sectional planes are distinguished in this work: section plane I corresponding to the \((\xi, \zeta)\) plane in Table 1 and section plane II corresponding to the \((\eta, \zeta)\) plane. In both sectional planes, the rolling elements and raceway represent non-concentric circular sections as electrodes. For these, a capacitance per length unit is to be calculated. Since this is scalable, one parameter can be eliminated effectively by representing the geometry without dimensions. Furthermore, the problem is generalized for the inner and outer ring by assuming a negative radius for the raceway radius on the inner ring \( r_{ij} \), from which negative dimensionless parameters \( \sigma \) and \( \tau \) result.

2.2. Different realizations of the semi-analytic approximation

To calculate the capacitance of areas outside the Hertzian areas of loaded rolling elements, the semi-analytical approximation is often used, Equation (3). The area is divided into plate capacitors of an infinitesimally small area \( dA = dx \, dy \) with variable height \( h \) and then integrated. However, this equation can be interpreted in various ways. For example, the arrangement of infinitesimal plate capacitors, as well as the integration limits, can be chosen in different manners. In this paper, three realizations of the 2D approximation according to Equation (2) are compared. The first method \( (dA) \), Figure 2 left) uses mutually parallel infinitesimal plate capacitors as e.g. described by Prashad [25]. In contrast to Prashad, however, a small-angle approximation

![Figure 1: Illustration of the deep groove ball bearing as a capacitance network.](image-url)
Table 1
Dimensionless contact geometry with raceway radius \( r \), distance between centre points of rolling element and raceway radius \( \sigma \), minimal distance between rolling element and race \( \alpha \) and race width \( \beta \).

| Section plane I | Inner race | Section plane II | Outer race |
|-----------------|-----------|-----------------|-----------|
| \( \tau = 2f > 0 \) | \( \sigma = \tau - 1 - \alpha > 0 \) | \( \tau = r_{a1}/r_{o1} < 0 \) | \( \sigma = \tau - 1 - \alpha < 0 \) |
| \( \beta = \frac{h}{2r} \) | \( \sigma = \tau - 1 - \alpha > 0 \) | \( \tau = r_{a1}/r_{o1} > 0 \) | \( \sigma = \tau - 1 - \alpha > 0 \) |

is not applied. The integration limits are chosen to be the groove width in section plane I and the rolling element diameter in section plane II.

For the second and third methods, Figure 2 right, the height \( h \) of the infinitesimal plate capacitors is chosen perpendicular to the rolling element surface. Method two (\( \int \mathrm{d}A_{\text{ball}} \)) then uses the surface element of the rolling element for the capacitance calculation, method three (\( \int \mathrm{d}A_{\text{race}} \)) on the other hand that of the raceway. Again, the groove width for the capacitance calculation, method three (\( \frac{\alpha}{2} \)), is selected as the integration limit for the outer ring.

\( \Phi(\phi, \Theta) = \frac{q}{4\pi\varepsilon} \ln \left( \frac{\rho^2 - 2\rho \cos \Theta \cos \kappa + 1}{\rho^2 - 2\rho \cos \Theta \cdot \kappa + \kappa^2} \right). \) (4)

Then, the potential field can be determined in dimensionless polar coordinates as

\( \Phi(\phi, \Theta) = \frac{q}{4\pi\varepsilon} \ln \left( \frac{\rho^2 - 2\rho \cos \Theta \cos \kappa + 1}{\rho^2 - 2\rho \cos \Theta \cdot \kappa + \kappa^2} \right). \) (5)

By forming gradients on the surface of the sphere (\( \rho = 1 \)), the electric field strength \( E_{\rho}|_{\rho=1} = -\frac{\partial \Phi}{\partial \rho}|_{\rho=1} \) can be calculated, which only has a radial component perpendicular to the electrode surface. Using the material law, the electric flux \( D_{\rho}|_{\rho=1} = \varepsilon \ E_{\rho}|_{\rho=1} \) and finally, using Gauss’ theorem, the charge per length unit \( Q' \) on the rolling element can be determined

\[ Q' = \frac{q}{\pi} \int_{0}^{\Theta_1} D_{\rho}|_{\rho=1} \, d\Theta = \frac{q}{\pi} \arctan \left( \frac{1 + \kappa \tan \left( \frac{\Theta_1}{2} \right)}{1 - \kappa} \right). \] (6)

The angle \( \Theta_1 \) is introduced as the integration limit in section plane I, which is calculated from the groove width \( \beta \) according to Figure 3.d

\[ \Theta_1 = \arctan \left( \frac{\beta/2}{\sqrt{\tau^2 - \beta^2/4 - \sigma}} \right). \] (7)
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Figure 3: Equipotential lines of the potential field of two line charges with indicated electrode contours a) in section plane I and in section plane II b) at the inner ring c) at the outer ring. d) Integration limit $\Theta_1$ in section plane I.

In section plane II, $\pi/2$ is the integration limit so that only the side of the rolling element facing the ring is included. Finally, the potentials of the two equipotential circuits are determined:

$$\Phi_{ball} = \frac{q}{2\pi\varepsilon} \ln \left| \frac{1}{\kappa} \right|,$$

$$\Phi_{race} = \frac{q}{2\pi\varepsilon} \ln \left| \frac{\tau - \sigma - 1/\kappa}{\tau - \sigma - \kappa} \right|.$$  \hspace{1cm} (8)

(9)

Now the capacitance of the arrangement can be determined:

$$C' = \frac{Q'}{\Phi_{ball} - \Phi_{race}} = 4\varepsilon \frac{\arctan \left[ \frac{\tan \left( \Theta_1/2 \right)}{1 - \kappa} \right]}{\ln \left| \frac{\tau - \sigma - \kappa}{(\tau - \sigma - \kappa + 1)} \right|}.$$  \hspace{1cm} (10)

Figure 4: Visualization of acceptable (left) and critical deflection (right) for the 2D calculation.

Figure 5: Geometries of the inner (left) and outer (right) race models used in the FE simulations.

2.4. Geometry and boundary conditions of implemented FE models

For complex geometries, an analytic solution can usually not be found. Instead, such geometries are modeled and simulated numerically. In this work, a single contact between a half ball and a raceway cut was simulated both in 2D for comparison with the analytical model with an in-house FE solver, and the full 3D geometry with the commercial simulation tool CST Studio. The geometry parameters were chosen from a 6205-C3 radial deep groove ball bearing on the inner and outer ring, Figure 5. The bearing ring is earthed in each case and a potential of 1 V is applied to the rolling element section. The boundary face in direction of the shaft or housing is grounded with the corresponding bearing ring. The axial faces are assumed to be free boundaries. All other edge faces of the model are assumed electrically insulating, which means that all electrical flux leaving the rolling element half flows to the bearing ring. The electrostatic solvers calculate the electric field and from this the charges $+Q$ and $-Q$ on the electrode surfaces. The capacitance then follows as $C = Q/(1V)$. 
3. Results and Discussion

3.1. Comparison of 2D results

First, the results of the 2D calculations, the analytical model according to section 2.3 and the numerical model, cf. Figure 5, are compared. Figure 6 shows the relative deviation of the semi-analytical as well as the FE simulation from the analytical solution for the capacitance per length unit of bearing 6205-C3. The distance between the raceway center and the rolling element is plotted on the abscissa. In the left diagram, it can be seen that the method of parallel infinitesimal plate capacitors (semi-analytical) underestimates the capacitance significantly. This is due to the fact that only the capacitor area projected in the $\zeta$ direction is taken into account and that with increasing distance from the center axis the height $h$ is no longer plotted at the shortest distance between the two electrodes. The deviation at larger electrode distances is due to slightly different boundary conditions at the groove edge: In the analytical calculation, this runs along the outermost field line of the electric field calculated in equation (7) and thus meets both, raceway and sphere surface, perpendicularly. The corresponding boundary in the 2D simulation (Figure 5 left), on the other hand, is approximated as a straight line perpendicular to the ball surface but not perpendicular to the raceway surface. The relative influence of this approximation rises with increasing electrode spacing, as the absolute capacitance decreases. However, the deviation in the considered range is small with about 0.01%.

The diagram on the right in Figure 6 shows an enlarged section of the diagram on the left. It is clear that the semi-analytical $\perp dA_{\text{ball}}$ and $\perp dA_{\text{race}}$ better approximate the analytically calculated results. When using the rolling element surface, the result is underestimated and when using the raceway surface, the result is overestimated, as the latter has the larger area.

Yet, the results of the 2D calculations are not directly transferable to the real ball-raceway contact. The 2D methods assume two eccentric cylinder surfaces for the electrodes while the real geometry consists of a sphere for the ball and a torus cut-out for the groove. Since an analytical solution for this problem is not found, the semi-analytical method $\perp dA_{\text{ball}}$ is compared with a FE simulation in section 3.4.

3.2. Influence of the rim area beside the groove

The semi-analytical method allows the consideration of not only the groove geometry, Figure 7 blue, but also the rim area beside the groove, Figure 7 yellow. A comparison of the calculated capacitance of unloaded rolling elements over a varying lubrication gap height is shown in Figure 8. For a bigger lubrication gap, the influence of the rim area increases. Since the rolling elements with a high lubrication gap height contribute rather little to the total capacitance, the rim area may be neglected for typical applications but should be considered for high precision calculations. Therefore, it is considered in this work for better comparability with the FE model which by nature considers this area.

3.3. Potential field retrieved from FE simulation

The resulting absolute values of the electric field strength as shown in Figure 9 indicate a very strong concentration of the electric field in the lubrication gap. At an exemplary lubrication gap of $5 \mu$m the field strength drops from the center to the edge of the groove by a factor of more than 10. As expected, the field strength outside the groove drops rapidly.
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Due to the increasing distance between the race and the ball, accordingly, the influence of boundary condition selection is low.

Figure 8: Comparison of capacitance over lubrication gap for the race and race+rim model for the inner and outer contact.

Figure 9: Electric field strength by 3D FE simulation in section plane I for the outer ring for the bearing 6205-C3 and an lubrication gap of 5µm.

Figure 10: Potential fields of the 3D FE simulation in section plane II for the outer (left) and inner (right) ring for the bearing 6205-C3 and an lubrication gap of 5µm.

Figure 11: Comparison of 3D FE-simulation results of inner and outer race of a 6205-C3 bearing with $\epsilon_{Oil} = 2.2$. For better comparability, equal groove geometries were used for the plots displayed.

3.4. Comparison of 3D results

The semi-analytical approximation $\perp dA_{ball}$ and the FE simulation are compared in Figure 12. The semi-analytical solution underestimates the FE simulation throughout. While the semi-analytic method gives a good estimation in section plane I, Figure 6, in section plane II, the accuracy is significantly less. On top of that, the simulation also takes stray capacitances into account, which are neglected in the semi-analytic method. It is also noticeable that the implemented method $\perp dA_{ball}$ increasingly underestimates the numerical solution with a rising lubricant film since here uncertainties of the approach become more relevant.

Figure 12: Comparison of 3D results for the inner race of a 6205-C3 radial deep-groove ball bearing with $\epsilon_{Oil} = 2.2$. 

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4. Conclusions

The capacitance of a rolling contact can – as shown – be calculated in various ways. In addition to FE simulations, semi-analytical approximations are widespread in the literature. There are different ways to interpret the infinitesimal plate capacitor method, Equation (3). Choosing the height of the infinitesimal capacitors perpendicular to the rolling element surface yields a more precise result than resorting to parallel capacitors. When deriving the area element size from the rolling element surface, more accurate results can be obtained, which, however, still significantly underestimate the real capacitance. The error increases with a rising lubrication film, thus, up to now the contribution of unloaded rolling elements, in particular, has been underestimated.

Numerical simulations also show that neglect of the raceway curvature results in significant errors and should be avoided whenever precise results are aspired.

The rim area as seen in Figure 7 can be included in the semi-analytical calculation although the benefit for the vast majority of applications might be negligible.

Furthermore, an analytical 2D calculation was presented to calculate the capacitances of the cutting planes in the deep groove ball bearing, taking into account the real electric field. An application of the equation to cylindrical roller, needle roller, or even plain bearings is also conceivable. Nevertheless, numerical methods remain the only sensible way to characterize the transient and non-linear behavior of rolling bearings and their lubricants.

CRediT authorship contribution statement

S. Puchtler: Writing – original draft, Methodology, Formal analysis, Visualization. T. Schirra: Investigation, Data Curation. E. Kirchner: Conceptualisation, Supervision. Y. Späck-Leigsnering: Writing – Review & Editing. H. De Gersem: Software, Supervision.

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References

[1] He F, Xie G, Luo J. Electrical bearing failures in electric vehicles. Friction 2020;8(1):4–28. doi: 10.1007/s40544-019-0356-5.
[2] Mütze A, Strangas EG. The Useful Life of Inverter-Based Drive Bearings: Methods and Research Directions from Localized Maintenance to Prognosis. IEEE Industry Applications Magazine 2016;22(4):63–73. doi: 10.1109/MIA.2015.2459117.
[3] Busse D, Erdman J, Kerkman RJ, Schlegel D, Skibinski G. Bearing currents and their relationship to PWM drives. IEEE Transactions on Power Electronics 1997;12(2):243–52. doi: 10.1109/63.558735.
[4] Mütze A. Bearing currents in inverter-fed AC-motors: Zugl.: Darmstadt, Techn. Univ., Diss., 2004. Berichte aus der Elektrotechnik; Aachen: Shaker: 2004. ISBN 3-8322-2528-5.
[5] Mütze A, Binder A. Calculation of Motor Capacitances for Prediction of the Voltage Across the Bearings in Machines of Inverter-Based Drive Systems. IEEE Transactions on Industry Applications 2007;43(3):665–72. doi: 10.1109/TIA.2007.895734.
[6] Gemeinder Y, Schuster M, Radnai B, Sauer B, Binder A. Calculation and validation of a bearing impedance model for ball bearings and the influence on EDM-currents. In: 2014 International Conference on Electrical Machines (ICEM 2014), Piscataway, NJ: IEEE. ISBN 978-1-4799-4389-0; 2014, p. 1804–10. doi: 10.1109/ICEMACH.2014.6960428.
[7] Furtmann A, Bader N, Poll G, Tischmacher H. Capacitances and Lubricant Film Thicknesses of Oil Lubricated Bearings. In: Bearing World Journal; vol. 2. Frankfurt am Main: VDMA Verlag; 2017, p. 43–7. URL: https://www.vdma-verlag.com/home/download/10987.html.
[8] Graf S, Sauer B. Surface mutation of the bearing raceway during electrical current passage in mixed friction operation. In: Bearing World Journal; vol. 5. Frankfurt am Main: VDMA Verlag; 2020, p. 137–47. URL: https://www.vdma-verlag.com/home/download/10987.html.
[9] Schirra T, Martin G, Vogel S, Kirchner E. Ball Bearings as Sensors for Systematical Combination of Load and Failure Monitoring. In: DS 92: Proceedings of the DESIGN 2018 15th International Design Conference. 2018, p. 3011–22. doi: 10.21278/idec.2018.0306.
[10] Schnabel S, Marklund P, Minami I, Larsson R. Monitoring of Running-in of an EHL Contact Using Contact Impedance. Tribology Letters 2016;63(3). doi: 10.1007/s11249-016-0727-2.
[11] Maruyama T, Maeda M, Nakano K. Lubrication Condition Monitoring of Practical Ball Bearings by Electrical Impedance Method. Tribology Online 2019;14(5):327–38. doi: 10.2474/trol.14.327.
[12] Schirra T, Martin G, Puchtler S, Kirchner E. Electric impedance of rolling bearings - Consideration of unloaded rolling elements. Tribology International 2021;158:109627. doi: 10.1016/j.triboint.2020.109627.
[13] Zhang X, Glovnea R. Grease film thickness measurement in rolling bearing contacts. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 2021;235(7):1430–9. doi: 10.1177/13506501209621278.
[14] Glovnea R, Furtuna M, Nagata Y, Sugimura J. Electrical Methods for the Evaluation of Lubrication in Elastohydrodynamic Contacts. Tribology Online 2012;7(1):46–53. doi: 10.2474/trol.7.46.
[15] Cen H, Lugt PM, Morales-Espejel G. On the Film Thickness of Grease-Lubricated Contacts at Low Speeds. Tribology Transactions 2014;57(4):668–78. doi: 10.1080/10402004.2014.957871.
[16] Jablonka K, Glovnea R, Bongaerts J. Quantitative measurements of film thickness in a radially loaded deep-groove ball bearing. Tribology International 2018;119:239–49. doi: 10.1016/j.triboint.2017.11.001.
[17] Prashad H. Theoretical evaluation of Impedance, Capacitance and Charge Accumulation on Roller Bearings Operated under Electrical Fields. Wear 1988;125:223–39.
[18] Barz M. Die Schmierfilmbildung in fettgeschmierten schnelllaufenden Spindellagern. Dissertation; Universität Hannover; Hannover; 1996.
[19] Furtmann A. Elektrisches Verhalten von Maschinenelementen im Antriebsstrang. Dissertation; Leibnitz Universität Hannover; Hannover; 2017. doi: 10.1177/13506501209621278.
[20] Baly H. Reibung fettgeschmierter Wälzlager. Dissertation; Universität Hannover; Hannover; 2005. doi: 10.15488/6495.
[21] Jablonka K, Glovnea R, Bongaerts J. Evaluation of EHD films by electrical capacitance. Journal of Physics D: Applied Physics 2012;45(38):385301. doi: 10.1088/0022-3773/45/38/385301.
[22] Witek E, Kriese M, Tischmacher H, Gattermann S, Ponick B, Poll G. Capacitances and lubricant film thicknesses of motor bearings under different operating conditions. In: The XIX International Conference on Electrical Machines - ICEM 2010. IEEE. ISBN 978-1-4244-4174-7; 2010, p. 1–6. doi: 10.1109/ICEMACH.2010.5688142.
[23] Bechev D, Kiekbusch T, Sauer B. Characterization of electrical lubricant properties for modelling of electrical drive systems with rolling bearings. In: Bearing World Journal; vol. Volume 3. Frankfurt am Main: VDMA Verlag; 2018, p. 93–106.
[24] Schneider V, Liu HC, Bader N, Furtmann A, Poll G. Empirical formu-

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lae for the influence of real film thickness distribution on the capacitance of an EHL point contact and application to rolling bearings. Tribology International 2021;154:106714. doi:10.1016/J.TRIBOINT.2020.106714.

[25] Prashad H. Tribology in electrical environments; vol. 49 of Tribology and interface engineering series. 1. ed. ed.; Amsterdam: Elsevier; 2006. ISBN 978-0-444-51880-4.

[26] Magdun O, Binder A. Calculation of roller and ball bearing capacitances and prediction of EDM currents. In: 2009 35th Annual Conference of IEEE Industrial Electronics. IEEE. ISBN 978-1-4244-4648-3; 2009, p. 1051–6. doi:10.1109/IECON.2009.5414869.

[27] Wolff I. Maxwellsche Theorie: Grundlagen und Anwendungen. 5., völlig neu bearb. und erw. aufl. ed.; Aachen: Wolff; 2005. ISBN 3922697313.