Experimental High Frequency Analysis of the Electric Impedance of Rolling Bearings

Presenter:

Georg Martin, M.Sc.
Fachgebiet Produktentwicklung und Maschinenelemente
Technische Universität Darmstadt

Additional Authors:
Tobias Schirra, M.Sc.; Prof. Dr.-Ing. Eckhard Kirchner
Fachgebiet Produktentwicklung und Maschinenelemente, Technische Universität Darmstadt

1. Introduction

The current trend in process monitoring and predictive maintenance propels the development of sensor-rich systems. Against this background, the authors investigate using bearings' electric properties as a sensor. This approach is based on electric impedance of bearings under an EHD regime, which depends on bearing load, speed and temperature. In an EHD regime, a non-conductive lubricant separates the surfaces of the rolling elements and the bearing rings. The electric model for every rolling contact is a plate capacitor, with the plates formed by the Hertzian area and the lubrication film thickness being the plate distance, as shown in Figure 1. In addition, the marginal area around the Hertzian area influences the electric impedance. Figure 2 shows a schematic design of such a sensor bearing. The lubrication film thickness depends on the temperature and rotational speed of the bearing [1]. Therefore, speed and temperature sensors are integrated into the sensory bearing. The electric measurement circuit needs to be isolated from the metal structure of the machine; the necessary isolating layers are shown by red lines in Figure 2. Finally, the electric impedance, temperature and rotation speed data are processed into information about bearing loads, lubrication condition and possibly bearing condition.

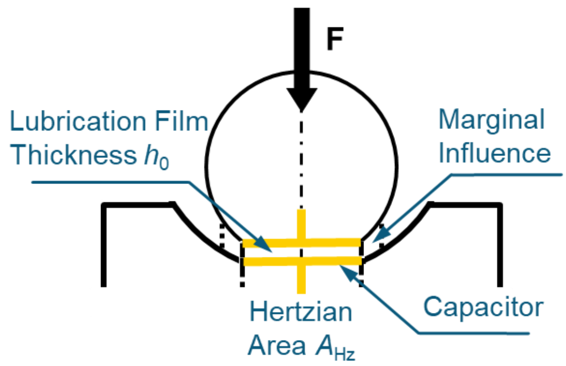

Figure 1:The rolling contact modelled as a capacitor depending on lubrication film thickness and Hertz'ian area

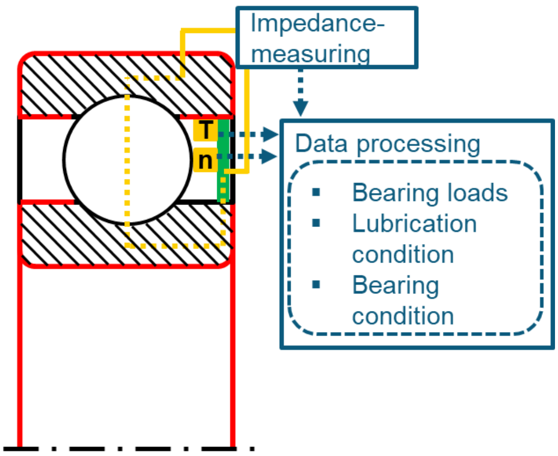

Figure 2: Load sensing bearing with insulating layer (red), connector (green), current flow (yellow) temperature (T) and rotation speed (n) sensor

Jablonka et al. [2] examined the electric properties of a bearing under radial load, which consisted only all ceramic rolling elements except one steel rolling element. Thus, they measured how the electric impedance depends on the position of the rolling element relative to the loaded zone. The impedance depends strongly on the position of the rolling element. The maximum impedance value occurs when the rolling element is in the center of the load zone. In a bearing consisting only of steel rolling elements, the total impedance consists of the impedances of all rolling elements. Therefore, the position of the rollers in the bearing has to be taken into account. In Figure 3, the two extreme states of rolling element positions in the bearing are shown. In one state (left), three rolling elements are loaded. One has maximum load, the others have a lower load. In the other load state, only two rolling elements are loaded, but they both have the same load. These states are associated with different values of the total impedance, between which the impedance value fluctuates while rotating. With a rotating inner ring and an outer ring at rest, the cage and the rollers rotate with two rotations of the inner ring. Thus the frequency f_c of the change of the electric impedance depends on the number of rollers z and the rotation frequency of the shaft n, assuming pure rolling. This frequency f_c is also known as the ball passing frequency at the outer ring (BPFO).

$$f_c = \frac{zn}{2}\left(1 - \frac{D_W}{d_m}\right) = 3.565\, n$$

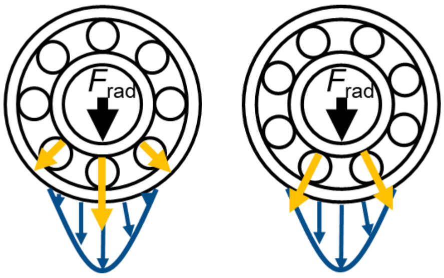

Figure 3: The two extreme states of roller position in roller bearings

2. Materials and Methods

The experiments for this study are done on the bearing test bench shown in Figure 4. Lubricant temperature, rotation speed and radial load are held constant for each measurement. An electric voltage *U* with frequency of 5 MHz and amplitude 1 V is applied between the inner and the outer bearing ring. The voltage *U* and current *I* are measured and the electric impedance is calculated with $Z = U/I$.

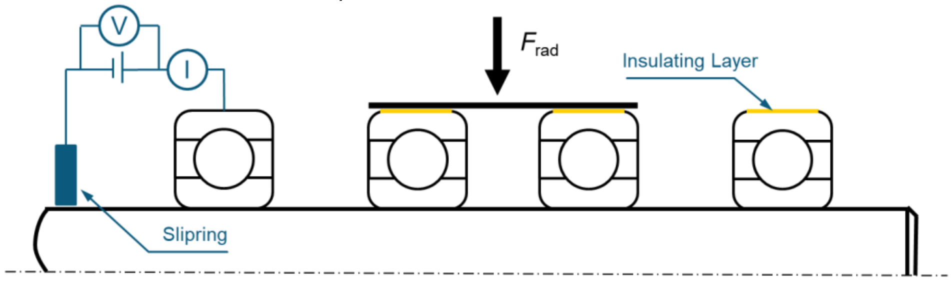

Figure 4: Bearing test bench

In Figure 5 an exemplary measurement result is shown. A periodic fluctuation between two impedance values is visible. The results are analyzed in the frequency domain. Figure 6 shows the FFT diagram of the measurement in Figure 5. Two significant amplitudes appear in the first and 3,6th order with reference to the speed of 1000 rpm.

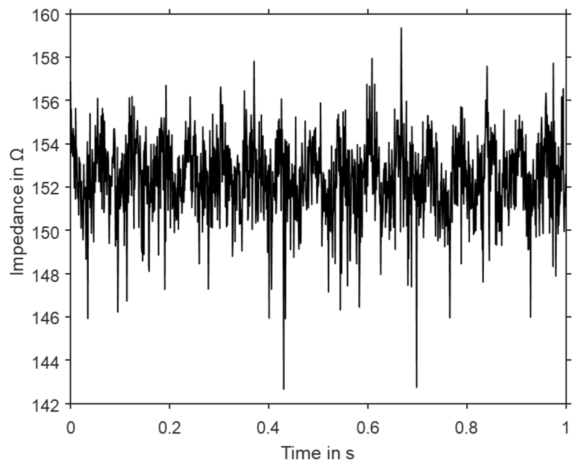

Figure 5: Measurement of the electric bearing impedance

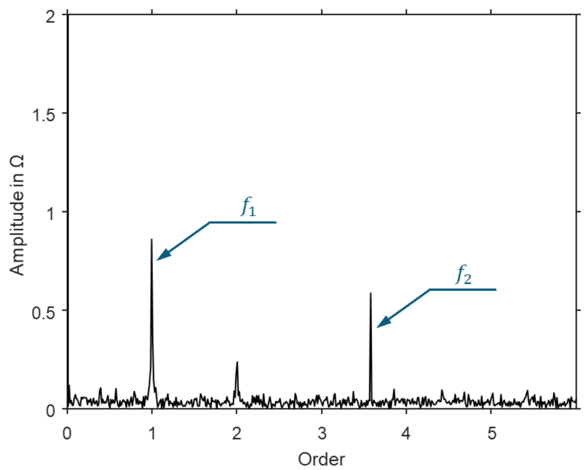

Figure 6: FFT of the measurement in Figure 5

3. Results

In this study, the influence of the parameters temperature, internal clearance, rotation speed and radial load on the frequencies f_1 and f_2 are investigated. The radial load varies from 750 N to 7000 N, the lubricant temperature varies from 30°C to 60°C and two types of internal clearance were tested (6205 C2 and 6205 C3). Temperature and internal clearance have no significant influence on the frequencies. On the other hand, the speed has a significant influence. Figure 4 shows the measured values for the two frequencies of the impedance signal at different values of rotation speed. The observation is a linear connection between the frequencies and rotation speed, with f_1 being equal to the rotational speed n and $f_2 \approx 3.6 \cdot f_1$.

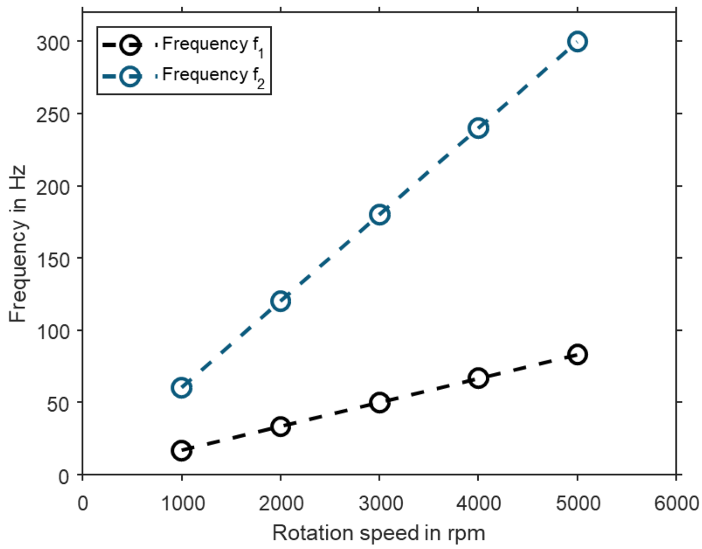

Figure 7: Measured frequencies f_1 and f_2 for different rotation speeds

In contrast to the expected single frequency f_c (see section 1), two different frequencies are observed. A possible explanation for the value of f_1 is an unbalanced shaft. The imbalance causes a load variation at the frequency of the rotational speed. The second frequency is f_c caused by the effect shown in Figure 3.

4. Discussion

The experiments in this study about the frequency spectrum of impedance signals of rolling bearings have shown that there is a connection between the frequency components and the rotation speed, and thus dynamics and kinematics of rolling bearings. The presented explanatory approach suggests that the rotational speed can be extracted from the impedance signal if the shaft is significantly unbalanced. The benefit for the sensory use of the electric effects in rolling bearings is that there is no need for an additional speed measurement anymore because the information is already contained in the measured signal. Further investigations could deal with a different number of rolling elements to validate the connection BPFO and the observed frequency f_2.

Acknowledgement

These experiments were performed using an EELPRAAX-80-4E test rig custom-built by Elgeti Engineering GmbH for this research. It is based on their standard bearing test rigs and allows time-dependent control of the axial load, radial load, speed, oil temperature and oil volume. A special feature of this particular rig is the ability to apply high-frequency AC currents in a targeted manner and to measure high-frequency voltages and currents. In order to accelerate the research process, the rig has four identical and independent testing stations.

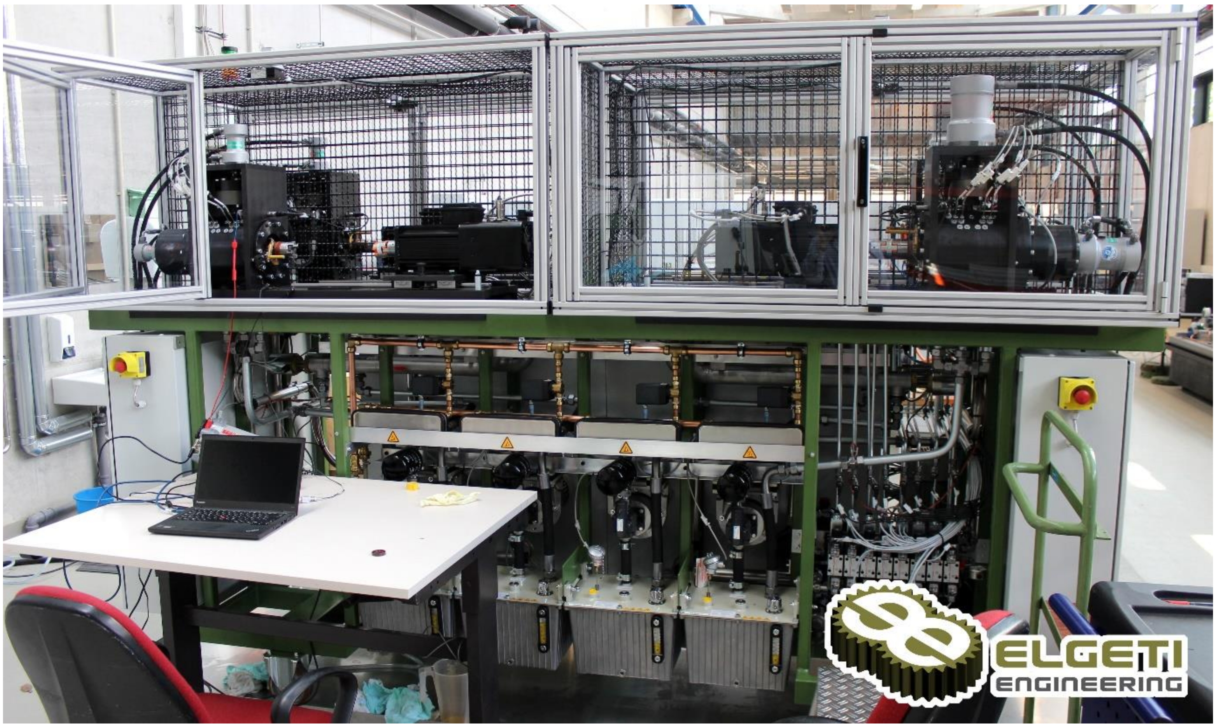

Figure 8: EELPRAAX-80-4E bearing test rig by Elgeti Engineering GmbH

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Literature

[1] Schirra, T., Martin, G., Vogel, S. a. Kirchner, E.: Ball bearings as Sensors for systematical combination of load and failure monitoring. Proc. DESIGN 2018, University of Zagreb, Croatia; The Design Society, Glasgow, pp. 3011–3022, 2018.

[2] Jablonka, K., Glovnea, R. u. Bongaerts, J.: “Quantitative measurements of film thickness in a radially loaded deep-groove ball bearing”. Tribology International 119 (2018) S. 239-249.

Georg Martin
Fachgebiet Produktentwicklung und Maschinenelemente TU Darmstadt

With company/institution since: 06/2016

Position:	**Research Associate**
Department:	**Mechanical Engineering**
Higher education/vocational training:	**Master of Science**

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