Physics Based Methodology for the Estimation of Bearings' Remaining Useful Life: Physics-Based Models, Diagnostic Methods and Experiments

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ABSTRACT

Rolling element bearing (REB) is one of the basic mechanical components in a rotating machinery. REBs' remaining useful life (RUL) estimation allows not only to assess time for maintenance actions but also can prevent a critical failure of the mechanical system. Usually, REB damage occurs in two stages, damage initiation and damage propagation. In the current work, it is assumed that spall is generated on the surface of the raceway during the initiation stage. The spall generation process is modeled based on continuum damage mechanics with the representation of material grain structure and implemented using a Finite Element (FE) software. The results of the model are in a good agreement with published theoretical and experimental data. However, after the first spall formation, the bearing might be fully operational for millions of cycles. For estimation of the bearing RUL it is important to understand the damage propagation process. The material behavior at the trailing edge of the spall during the rolling element (RE) impact is analyzed. The analysis is carried out by using a hybrid modeling approach. This approach integrates non-linear dynamic modeling and FE simulations. The paper also includes a discussion on the ongoing research and the methodology for the development of the prognostic method. Implementation of the proposed methodology has the potential to provide a complete estimation of the bearing’s RUL: from first spall formation to the un-operational bearing.

1. INTRODUCTION

Machinery diagnosis and prognosis is the machine’s forecast of the remaining operational life, future condition, or probability of reliable operation. The process includes using

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model assembly, towards a realistic representation of the grain topology and microscopic failure, using standard FE software tools. By using the suggested method the fatigue life of the REBs are calculated and analyzed using a two-parameter Weibull distribution function. Furthermore, the micro-cracks formation and spall generation are simulated. The results of the damage initiation model show a good agreement with previously published data.

Prediction of the damage propagation in the REB, after the first spall generation, is not an easy task. The difficulties in prognosis of the propagation stage necessitate the deep understanding of the damage mechanisms, the stochastic nature of the spall propagation process, and its modeling (Kotzalas & Harris, 2001, Li et al., 1999, Qiu et al., 2002). The main goal of the future research is to develop a physics-based prognostic method for the spall propagation in the REB. The first step towards this goal is the understanding of the material response after the first spall generation. For the purpose of the material analysis, a model for the RE-spall edge impact simulations was developed. The simulation results have the potential to yield insights into the understanding of the damage mechanism governing the spall propagation. Moreover, the development of the method depends on the implementation of the research objectives and suggested methodology that are described and discussed in the second part of this paper.

2. DAMAGE INITIATION

This section presents assembly and application of the damage initiation model for an ideal line contact, by using with the damage accumulation model for different grain topologies. The procedure of the model assembly includes three stages: contact loading, microstructure formation, and damage modeling. The contact between the raceway and the roller represented by the classic Hertzian solution (Harris & Kotzalas, 2006, Jackson & Green, 2005, Timoshenko & Goodier, 1984). The microstructure is represented by a Poisson Voronoi tessellation with variations in the material properties. The damage process is simulated using the elastic damage accumulation model, mostly based on the works published by Slack and Sadeghi (2010), and Warhadpande, Sadeghi and Kotzalas (2012). The three analysis stages were implemented using a FE software.

2.1. The contact model

The Hertzian solution for an ideal line contact in a cylindrical roller bearing was used to represent the contact between the RE and the raceway (Gazizulin et al., 2015), as shown schematically in Fig. 1(a). The surface compressive traction distribution \(p(x)\) within the line contact area is given by

\[
p(x) = p_{\text{max}} \left(1 - \frac{x^2}{b^2}\right)^{1/2} \tag{1}\]

where \(p_{\text{max}}\), \(b\) and \(x\) are the maximum pressure at the middle of the pressure profile, the half width of the contact area, and the local coordinate, respectively, illustrated in Fig. 1(a). The cyclic rolling contact of RE was simulated by setting the Hertzian contact at initial location (Init. Loc.). Next, it was advanced in discrete steps to the final position as shown schematically in Fig. 1(b).
2.3. The Damage Accumulation Model

One microscopic mechanism of RCF damage is the formation and coalescence of microcracks. Continuum damage mechanics (CDM) provides a representation of these microscopic failure mechanisms by the definition of a nondimensional damage variable \( D \). It is assumed that the damage variable \( D \) affects the elastic modulus \( E \) of the material as

\[
\overline{E} = (1 - D) E
\]

where \( \overline{E} \) is the damaged elastic modulus. The presence of the damage reduces the material stiffness (Chaboche, 1988, Marble & Morton, 2006). The damage variable \( D \) has values ranging from 0, which represents undamaged material, to \( D_{\text{max}} \), which represents a completely damaged material, and its maximum value can be 1:

\[
0 \leq D \leq D_{\text{max}}
\]

The general form of the non-linear equation for damage rate evolution is

\[
\frac{dD}{dN} = f(\sigma, D)
\]

where \( N \) is the number of stress cycles and \( \sigma \) is the critical stress causing the damage. For RCF problems the critical stress is an orthogonal shear stress range \( \Delta \tau_{xy} \) (Chen et al., 1991). If the material point undergoes a purely elastic damage, then the damage rate evolution is given by

\[
\frac{dD}{dN} = \left[ \frac{\Delta \tau_{xy}}{\sigma_r (1 - D)} \right]^m
\]

where \( \Delta \tau_{xy} \) is the orthogonal shear stress range measured during the load cycles, and \( \sigma_r \) and \( m \) are material-dependent parameters that are empirically determined (Slack & Sadeghi, 2010, Warhadpande et al., 2012).

2.4. The Simulation Results

After modeling each of the physical properties and phenomena separately, all three were integrated in order to simulate the damage initiation process. The number of cycles elapsed until the first microcrack is termed the initiation time. Subsequently, the simulation continues via the generation of additional microcracks, which coalesce to form a crack. The crack propagates; and when it reaches the surface, it forms a spall. At this point, when the spall is generated, the simulation stops, defining the total time (Gazizulin et al., 2017).

Twenty microstructures were constructed and the RCF process was simulated with a \( D_{\text{max}} = 0.95 \). The values of different coefficients and parameters are presented in (Gazizulin et al., 2017). The results of the fatigue lives and the corresponding Weibull probability plot are presented in Fig. 3. An example of crack initiation and propagation in the microstructure, and the representative spall pattern are presented in Figs. 4 and 6, respectively. The first microcrack initiated near the location of the maximum orthogonal shear stress, \( y = -0.5b \), which corresponds to the experimental results achieved by Chen et al. (1991). From Fig. 3, it can be seen that the RCF process is dominated by the initiation stage, whereas the average duration of the propagation stage is only 12% of the total life. This result is consistent with the results obtained by Slack and Sadeghi (2010) and Warhadpande et al. (2012). The microcracks generated during the RCF simulations and the propagation process show good agreement with experimental observation described by Meyer et al. (2003) and presented in Fig. 5. Each simulation resulted in a unique spall shape due to different grain topologies and variation in the material properties. However, the general shape of the spall obtained from the simulations is in good agreement with the results presented by Slack and Sadeghi (2010) and Warhadpande et al. (2012), and with experimental spallation (Fig. 6).
Bearing fatigue lives are stochastic in nature; therefore, it is very common to use the Weibull distribution to describe the fatigue lives of bearings. The results of the total time are displayed on the Weibull probability plot in Fig. 3(b), where the slope, $\beta$, is $5.77$. According to Harris and Kotzalas (2006), for modern, ultra-clean, vacuum-remelted steels, the values of the Weibull slope should be $0.7 \leq \beta \leq 3.5$. The achieved slope, $\beta = 5.77$, is outside this range. The difference can be explained by the simplifications in the assumed material properties. However, the achieved slopes, for the initiation and the total time, are very close to the results of the previously published models (Raje et al. (2009), Slack and Sadeghi (2010), Jalalahmadi and Sadeghi (2010), Warhadpande et al. (2012)).

The first objective is the quantitative and qualitative understanding of the damage-driven mechanisms, e.g. plastic strains, residual stresses, etc., of the spall propagation process (Bolander et al., 2009, Branch et al., 2009, Marble & Morton, 2006, Morales-Espejel & Gabelli, 2015). In addition, it is important to acquire knowledge, based on the existing literature and experiments, about the effects of the bearing’s features (e.g. hardness, ball mass), and operational conditions (e.g. speed, load) on the propagation process and the trend of the spall growth (Arakere et al., 2009, Branch et al., 2013, Morales-Espejel & Gabelli, 2015). For this purpose, an experimental setup was designed (Fig. 7) and endurance tests were conducted. During the tests, the degradation of the REB was monitored using different types of sensors. Based on the test results the health degradation trends were built. Examples of the test results are shown in Figs. 8 and 9. The tests add insight about the spall propagation process and can be used for the physical model calibration, i.e. estimation of the model parameters, and later for validation.
3.2. Damage Propagation Model

The second objective is the development of a model for the prediction of the damage propagation process. First, the material response in the presence of a defect must be analyzed. This analysis, coupled with the endurance test results, will shed light on the mechanism governing the damage propagation process. A model for the RE-spall edge impact simulations was developed. It integrates a non-linear dynamic (Kogan et al. 2016) and FE models, Fig. 10. The model is used for the evaluation of the stress/strain fields within the spall edge as a result of RE impact, Fig. 11. Next, to simulate the damage propagation process, the results of this analysis will be used as an input to the damage model. The accomplishment of this objective will provide a mean estimated damage trajectory. However, the damage propagation is a stochastic process. Hence, the results will have some degree of uncertainty.

3.3. Stochastic Nature of the Damage Growth Process

The third objective of the research, and probably the most challenging one, is to model the stochastic nature of the damage propagation. The propagation of the spall in the REB is a highly varying process. Even under well controlled experimental conditions, using allegedly identical bearings, the results of the endurance tests vary (Rosado et al., 2009). The RUL estimation must consider the uncertainties and their propagation. One of the common methods for dealing with this challenge is to use diagnostic condition indicators in the early stages of the damage in order to monitor its propagation, e.g. oil debris, vibration level, etc. An example of a diagnostic indicator evolution vs. time is shown in Fig. 9. Also, in our laboratory, we have a diagnostic tool for the spall width measurement via time domain analysis of the acceleration signature (Kogan et al. 2016). The data from diagnostic indicators will be used for the estimation of the damage model parameters by the trend identification of the spall propagation process. Afterward, using the adjusted model...
parameters to the specific spall propagation process in the damage model, the RUL will be estimated. It is important to understand that the measured data will be dispersed around the trend with some variance. Thus, in addition to the RUL estimation, its distribution should be determined. The RUL process estimation is schematically illustrated in Fig. 12. The accomplishment of this goal will complete the development of the physics-based prognostic method.

![Figure 12. Bearing prognosis: first the damage propagation process is monitored, the model parameters are estimated and the RUL is calculated.](image)

4. METHODOLOGY

The proposed methodology for the development of the prognostic method is based on a combination of physics-based models, diagnostic methods and experiments. This approach consists from procedures and techniques which are described below. The spall initiation process, described previously in this paper, was successfully implemented and verified using the FE software ABAQUS. Next, the FE and dynamic models of the spalled bearing were used to yield the dynamic response, stress and strain histories of the spalled bearing. These results can be used as input for the damage propagation model. Furthermore, the spalled bearing model might be used for the validation of the diagnostic method for the damage severity estimation.

Figure 13 illustrates the integration of different steps described above for the REB’s RUL estimation. Calibration and Validation of the spalled bearing model can be implemented by comparing the simulations results with the data extracted from endurance tests. For example, a diagnostic method for the defect severity estimation (fault size, vibration level, etc.) can be implemented during the first stages of the tests. The results obtained by the diagnostic method can be used for the estimation of the damage model parameters and their uncertainties. Then, the integration of the prognostic and the diagnostic methods, has the potential for the online estimation of the RUL including probability distribution of the result.

5. SUMMARY AND CONCLUSION

A process has been presented for developing and implementing a damage initiation model representing spall generation in REB during RCF. The procedure of the model assembly comprises three stages: contact, microstructure, and damage modeling. The contact is modeled using the Hertz solution; the microstructure is represented by a Poisson Voronoi tessellation; and the damage accumulation model is based on CDM. Model implementation was carried out using standard tools of the FE software, i.e., meshing process, damage representation, etc. The results achieved from the simulation are in a good agreement with previously published work and what has been observed experimentally. The paper also suggests a methodology for the REB’s RUL estimation. It includes understanding and implementation of different steps: endurance tests, physical understanding of the spall propagation process and its stochastic nature, damage and bearing modeling, etc. Eventually, accomplishment of these steps will help to build a prognostic tool.

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REFERENCES


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**Dmitri Gazizulin** received his B.S. and M.S. degree in Mechanical Engineering from the Ben-Gurion University of the Negev. Currently, he is a PhD student. His study focuses on the rolling element bearing failure prediction by using physical based models. His main areas of research interest are rolling contact fatigue, finite element modeling, vibration and strain based diagnostics and prognostics systems, and endurance tests.

**Dr. Renata Klein** received her B.Sc. in Physics and Ph.D. in the field of Signal Processing from the Technion, Israel Institute of Technology. In the first 17 years of her professional career, she worked in ADA-Rafael, the Israeli Armament Development Authority, where she managed the Vibration Analysis department. In the decade that followed, she focused on development of vibration based health management systems for machinery. She invented and managed the development of vibration based diagnostics and prognostics systems that are used successfully in combat helicopters of the Israeli Air Force, in UAVs and in jet engines. Renata is a lecturer in the faculty of Aerospace Engineering of the Technion, and in the faculty of Mechanical Engineering in Ben Gurion University of the Negev. In the recent years, Renata is the CEO and owner of R.K. Diagnostics, providing R&D services and algorithms to companies who wish to integrate Machinery health management and prognostics capabilities in their products.

**Prof. Jacob Bortmann** joined the academic faculty of Ben-Gurion University of the Negev in September 2010 as a full Professor. Prof. Bortman spent thirty years in the Israel Air Force (IAF), retiring with rank of Brigadier General. His areas of research in the Dept. of Mechanical Engineering include: Health usage monitoring systems (HUMS); Conditioned based maintenance (CBM); Usage and fatigue damage survey; Finite Element Method; and Composite materials.