Steps toward prognostics of faults in bearings

Eyal Madar [1], Gideon Kogan [2], Dmitri Gazizulin[3], Renata Klein[4], and Jacob Bortman [5]

[1,2,3,5]*Pearlstone Center for Aeronautical Engineering Studies and Laboratory for Mechanical Health Monitoring, Department of Mechanical Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer Sheva 8410501, Israel*

eyalmad@post.bgu.ac.il
genak@bgu.ac.il
dmitrig@post.bgu.ac.il
jacbort@bgu.ac.il

[4]*R.K. Diagnostics, P.O. Box 101, Gilon, D.N. Misgav 20103, Israel*

renata.klein@rkdiagnostics.co.il

Abstract

Assessment of the remaining useful life of a rolling-element bearing is a key element in rotating machines prognostics. Evaluation of the bearing remaining useful life (RUL) requires diagnosis of the fault existence, estimation of its size and estimation of the time interval until it reaches a critical size. A concept for bearing RUL estimation is proposed. The main insights which led to the concept development are reviewed. The study focuses on estimation of spall size located in one of the bearing races. A new approach for estimation of spall size in bearing races is developed based on physical insights obtained from results of a general bearing dynamic model. Analytical modeling of the interaction between the spall and the rolling element enables the development of an autonomous generic method for spall size estimation. In this paper the principles for spall size estimation are described. The new method was applied to experimental data including different spall sizes on inner and outer races. The estimation shows satisfactory results with errors up to 20%.

1. Introduction

Prevention of failures of bearings is a subject of great interest for maintenance of rotating machines. For failure prevention, it is necessary to monitor the current state of the bearing and also to estimate the amount of time remaining until the bearing reaches a critical failure (RUL).

For successful assessment of the bearing remaining useful life, it is essential to understand the bearing deterioration process. Additionally, it is necessary to evaluate the current condition of the bearing and identify faults as early as possible.

Methods for bearing prognostics and diagnostics can be divided into two main categories, physics-based and data-based (Heng, Zhang, Tan, & Mathew, 2009). Currently, most of the methods for spall size estimation are based on time domain analysis of the acceleration signal (Epps, 1991, Petersen, Howard, Prime 2015, Sawalhi & Randall 2011, Zhao, Liang, Wang, Zhang 2013, Cui, Wu, Ma, Wang 2016). These methods are specific, not autonomous and require expert involvement. Furthermore, the studies were focused on faults in bearing outer race.

The proposed approach is physics-based and can be used for different bearing faults. This paper presents the approach for local faults on one of the bearing races. The approach includes integration of dynamic model results and seeded test experiments. First a general dynamic model of a bearing was build. The model solves numerically the dynamic equations describing the behavior and the interactions between the rolling elements and the races in healthy conditions or with faults. The signals simulated from the models established the physical understanding of the processes that occur during the bearing life. Additionally, prominent events in the simulated acceleration signal during the RE-spall interaction were investigated. Various experiments were performed and the measured signals were analyzed. The insights from the simulation allow a better interpretation of the experimental signals and development of diagnostic and prognostic methodology. Similarly, the experimental signals are used to verify the model and to learn the deficiencies in the model.

The elements of the approach towards prognostics of bearings include: a physical model of the spall initiation, modeling of the bearing dynamics, modelling of the bearing deterioration process and estimation of spall size. Based on the physical insights from the models and the existence of identifiable events in the measured signal, a new method for spall size estimation was developed. The goal was to develop an autonomous, physical based method for bearing prognostics, which requires parameters related only to the system operation conditions and geometric characteristics of the bearing.

2. BEARING DETERIORATION PROCESS

The deterioration process of a bearing consists of three main stages (Gazizulin, Klein and Bortman, 2017), as displayed in Figure 1 (separated by vertical black lines). The first stage, Damage Initiation, is characterized by the initialization of microcracks inside the raceway of the bearing. The initialization of the microcracks does not cause significant change in the vibration signal and in this stage, it is difficult to identify or quantify the damage. In the second stage, Steady Damage Propagation, the microcracks grow to larger cracks and propagate towards the surface of the bearing race. When the microcracks reach the surface, part of the material is detached and a spall is generated. After the formation of the spall the machine still works properly, but, as the machine continues to work, the spall grows. Detecting the formation of a spall at this stage is still not possible. Therefore, the minimum identifiable spall size is derived by the prominence of the spall in the vibration signature and the ability to recognize it. In the final stage, Accelerated Damage Propagation, the damage propagation is accelerated and eventually causes the machine to break down.

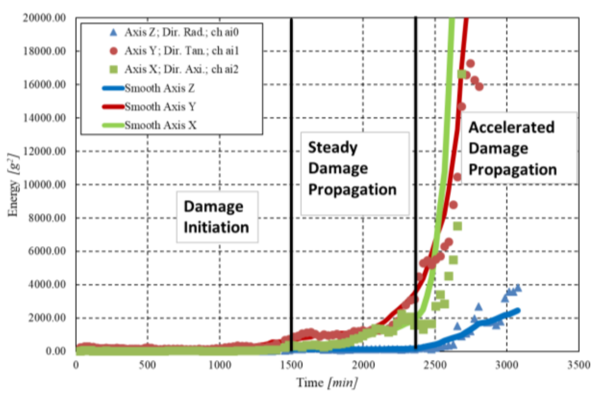

Figure 1. Trend lines of the acceleration from a bearing endurance test (Gazizulin et al. 2017).

Figure 1 presents the vibration energy related to the monitored bearing during an endurance test. The change in energy is related to the bearing deterioration level. However, the measured vibration energy is significantly affected by the bearing condition, system operating condition and the transmission path. Hence, for each monitored bearing the energy trend line will have a different range of the energy levels. For linking the value of the energy level to the damage severity (spall size) it is necessary to evaluate the transmission path effect, which would require a specific model for each case (machine, bearing fault, operation condition and sensor location).

The prognostics research focuses on generating a physical based model which connects between the bearing state and the remaining time until the bearing reaches the third stage of the deterioration. It should be emphasized that until a defect is discovered the bearing is treated as healthy (the first stage - Damage Initiation).

To be able to estimate the RUL it is necessary to assess the current state of the bearing. However, detecting the presence of a defect and its type is not enough for RUL estimation. The defect severity must also be considered and monitored to characterize the rate in which the defect is developed. Hence, estimation of spall size in bearing outer and inner races based on vibration signature is required.

3. CHARACTERIZATION OF FAULTS USING ENERGY LEVELS

Initial work on the relationship between vibration energy and fault size was described in Mendelovich, Sanders, Kogan, Battat, Klein and Bortman (2014). This study used envelope analysis which is the conventional analysis common in bearing diagnostics. The envelope of the acceleration emphasizes the signals related to the bearing. Hence, the change in the RMS value of the envelope, is considered to represent mainly the bearing state. The research was based on a general bearing dynamic model simulating cases of bearings with and without faults (Kogan, Klein, Kushnirsky and Bortman, 2015).

Different bearing fault sizes were simulated with the dynamic model. Figure 2 shows the simulated relation between the RMS levels of the envelope and the fault size. It should be noted that the model is simulating the acceleration of the bearing races without considering the transmission function to the sensor.

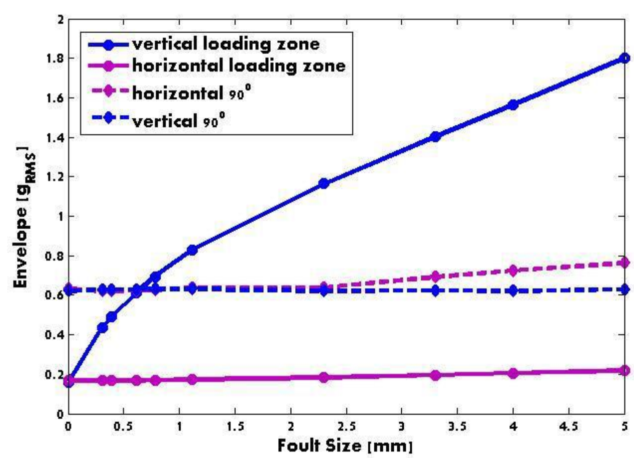

Figure 2. Model based results: RMS levels of envelope acceleration as a function of the fault size (Mendelovich et al. 2014).

It was found that in some of the simulated configurations, the RMS level is growing with the fault size. In contrast, in the measured signal (Figure 3) the RMS value did not show the same behavior. The discrepancies between the simulation levels and the measured levels can be explained by the absence of the transmission function in the model. In real situations, the measured signal is affected by the transmission function between the defect and the sensor. The acceleration trend line (Figure 1) varies for each combination of bearing, system, running conditions and measurement position. The deterioration severity of the fault cannot be monitored without modeling the transmission function and it is impossible to build a generic model for the transmission function.

The levels of the envelope acceleration can be used for detection of faults and for characterization of the fault type (in outer or inner race or on the rolling elements). However, for fault severity estimation this is insufficient.

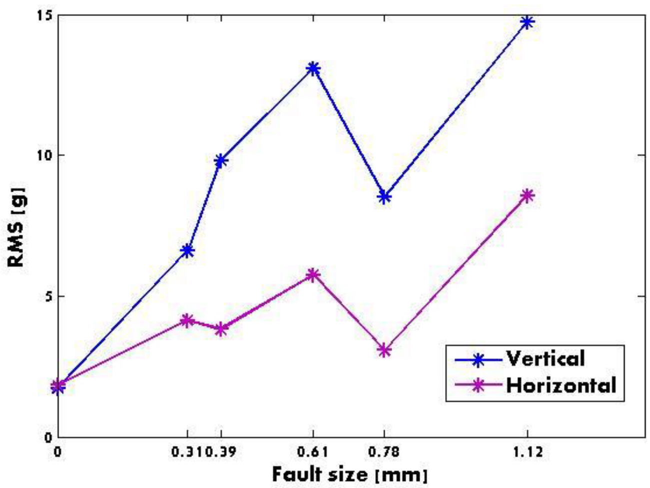

Figure 3. Experimental based results: RMS levels of envelope acceleration as a function of the fault size when fault located at the center of the loading zone (Mendelovich et al. 2014).

Based on these insights it was concluded that a different approach should be established for evaluation of fault severity. The new approach will complete the damage identification for prognostics, and should be applied only after the damage was identified.

The severity assessment method must meet several requirements. First, features which correlate with the severity of the fault should be extracted. The method need to be generic, i.e. independent of the specific machine, location of the sensor (transmission path) or location of the fault. The method should consider only the system operating conditions and bearing geometry, i.e. a method which does not depend on empirical data for RUL estimation.

4. PHYSICS BASED APPROACH

The main drawback of the methods based on vibrations energy for fault size estimation in bearings is the inability to connect between the energy levels and the fault size. A deep understanding of the physics of the interaction between the RE and the fault is essential for successful fault size estimation.

In the first step toward physics based fault size estimation, a thorough study was conducted on the simulations from the general bearing dynamic model. The physical insights from the model simulations were used to determine the principles of a new method for fault size estimation, which will be described.

4.1. Spalled bearing simulations results

The researched cases are a spall located in bearing outer race and a spall located in bearing inner race. At that stage of the research, it is assumed that there is only one race which is spalled and the inner race rotates while the outer race is static.

In previous research (Epps, 1991) it was found that during the RE-spall interaction two events occur, the entrance and exit of the RE from the spall. A simulated acceleration signal of a bearing with spall in the outer race and inner race is presented in Figure 4 and Figure 5 respectively. The entrance and exit events are clearly visible. The black mark corresponds to the contact of the RE with the spall entrance edge and the red corresponds to the contact of the RE with the spall exit edge. However, for estimation of the spall size, an expression connecting the spall size with the time lag between the two events should be developed. Automatic identification of the events would require characterization of the entrance and exit events.

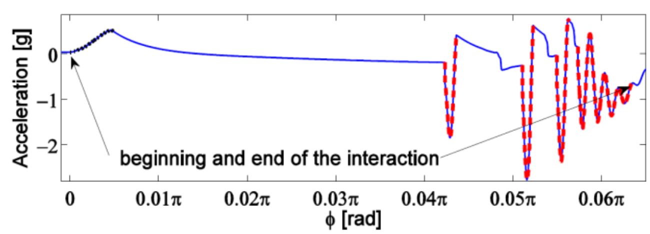

Figure 4. The simulated acceleration of the outer race. Spall in the outer race: blue solid– simulated signal; black doted – RE-entrance edge contact; red – RE-exit edge contact. (Kogan, Madar, Klein and Bortman, 2016).

Examination of the simulations shows that the RE-spall interaction can be divided into three parts. The first part is the entrance of the RE into the spall where the acceleration signal behaves as a typical response to a step function. After the RE disconnection from the spall entrance edge, the outer race acceleration starts to decay, this is the second part of the RE-spall interaction where the RE is detached from the races. The last part is the collision of the RE with the spall exit edge. The acceleration signal response to the exit event varies in accordance to the spalled race. In the case of a spalled outer race the RE rattles between the inner and outer races before the exit causing a series of impacts. For a spalled inner race the exit event is a typical response to a step function similar to the entrance event. In addition to the aforesaid, for the case of a spall in the inner race, and while the RE is detached from the races, the gravitation and centrifugal forces might cause the RE to drop back to the outer race and strike several times (green in Figure 5). The number of strikes depends on the spall size, bearing geometry and the operating conditions. The response function to these strikes can mask the exit event in the measured acceleration signal.

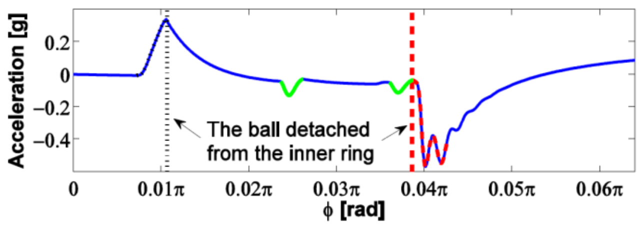

Figure 5. The simulated acceleration of an interaction. Spall in the inner race: blue solid– simulated signal; black doted– RE-entrance edge contact; red dashed– RE -exit edge contact; green solid: RE -outer race contact during the interaction. (Madar, Kogan, Klein and Bortman, 2016).

The difficulty in identifying the location of the entrance and exit events in a measured signal can be understood from examination of the simulated signal (Figure 4 and Figure 5). Several factors must be considered while assessing the time of occurrence of the events. The events do not have prominent characteristics in the signal. Additionally, the noise levels and the transmission path to the accelerometer may mask the events location and those should be separated.

The insights from the RE-spall interaction formed the basis for development of two analytical dynamic models, one for the interaction between the RE and a spalled outer race (Kogan, Bortman and Klein 2017) and a separate model for the interaction between the RE and a spalled inner race. The analytical models produced an explicit relation between the spall size and the time between the RE disconnection from the spall entrance edge and the collision with the spall exit edge. The developed expressions took in consideration the system operation condition and the bearing geometric characteristics. The expressions developed for spalled outer race are presented in equation (1).

$$\Delta s = \sqrt{2R_{RE}\delta} + \frac{\omega_c D_p}{2} t_{imp} + \sqrt{R_{RE}^2 - h^2} \tag{1}$$

where R_{RE} is the RE radius, δ is the initial deflection of the RE into the inner race, ω_c is the cage rotational speed, D_p is the bearing pitch diameter, t_{imp} is the time interval between the RE disconnection from the spall entrance edge and the collision with the spall exit edge and h is the vertical distance between the center of the RE and the outer ring surface which is calculated using equation (2)

$$h = \delta - R_{RE} + \omega_c D_p \sqrt{\frac{\delta}{2R_{RE}}} t_{imp} + \left(g + \frac{D_p}{2}\omega_c^2 \right) t_{imp}^2 \tag{2}$$

where g is the gravitation acceleration.

In a similar way, an expression for the case of a spalled inner race which took in consideration the system operation condition and the bearing geometric characteristics was developed (Madar, Kogan, Klein and Bortman 2017).

4.2. Spall size estimation method and experiment results

The physical insights reviewed in the previous section constituted the basis for definition of a new method for spall size estimation in bearing races (Madar el al. 2016). This method was tested on bearings with a spalled race, inner or outer. Results of the new method are presented in this section.

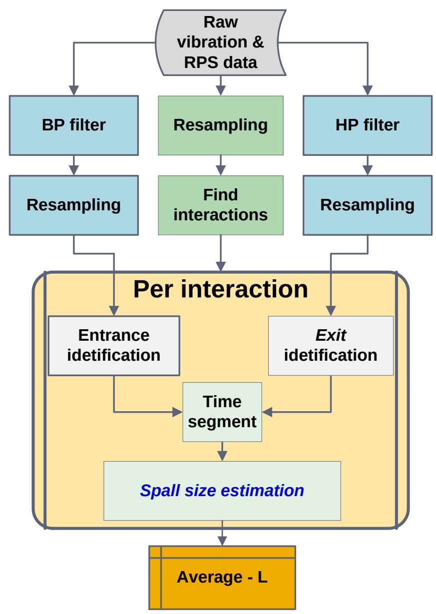

Figure 6. Block diagram of the method for estimation of the spall size (Madar el al. 2016).

The proposed method for estimation of the fault size is applied to the measured acceleration signal. The method is designed to estimate the size of spall-like faults in both bearing inner and outer races on the RE path.

The method is divided into four steps. In the first step the valid and relevant RE-spall interactions are automatically selected. In the second step, the measured signal is filtered by two filters, a band-pass filter to locate the RE entrance into the spall and a high-pass filter to locate the RE exit from the spall. The filter frequencies are calculated using the analytical model results for each bearing geometry and operation condition. In the third step, the time interval between the two events is measured. In the fourth step, the spall size is calculated using the explicit relation between the time interval and the spall size. The block diagram of the method is shown in Figure 6. Using this method, a new algorithm for spall size estimation was defined. The algorithm is designed to operate automatically given the system operation condition and the bearing geometric characteristics.

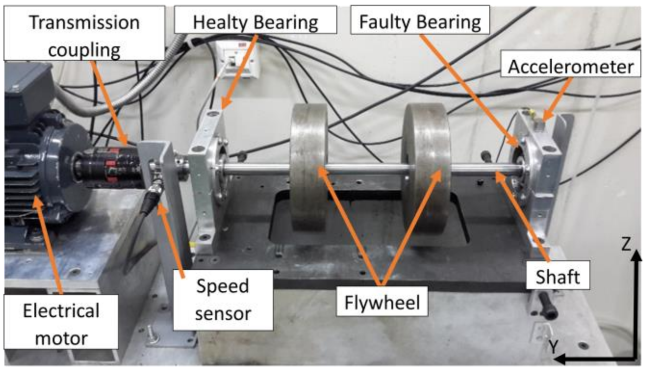

Figure 7. The test rig.

A preliminary version of the algorithm was applied to measured acceleration signals acquired from a test rig (Figure 7) in which one of the bearing races was artificially spalled. Furthermore, different spall sizes were tested. The estimation results show errors of up to 20% (Figure 8).

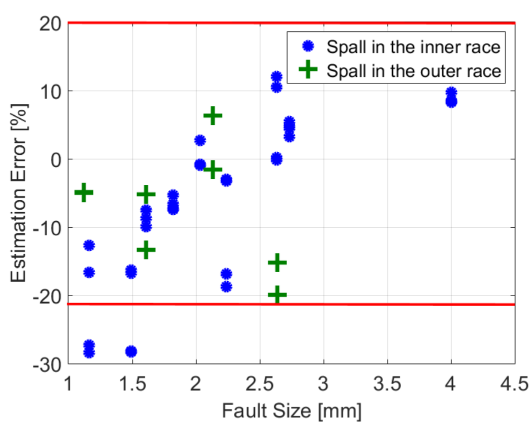

Figure 8. Relative error of the method estimated spall size versus the optical measurements of the spall.

5. CONCLUSIONS

Identification of spall existence does not provide sufficient information for decision on scheduling a maintenance operation. The presented study is part of an ongoing research on bearing prognostics, i.e. prediction of the bearing RUL. Thus, it is crucial to monitor the bearing state in real time. The bearing state is defined by the fault existence and its severity. Besides fault detection, the fault progression modeling is essential for estimation of the bearing remaining useful life. Therefore, spall size estimation is the focus of this study.

Based on insights from a general bearing dynamic model and expressions from an analytical model of the rolling element - spall interaction, a new method for estimation of spall size is proposed. The method is designed for determination of spall size on the inner or outer race but could be expanded for other bearing faults. It requires only definition of the bearing geometry and operating conditions and it is autonomous. Experiments on several spall sizes on inner and outer races were conducted. The method results validate the new approach which forms the basis for further research.

6. ACKNOWLEDGEMENTS

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