Remaining Useful Life Prognostics of Rolling Element Bearings Based on State Estimation Techniques

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ABSTRACT

Rolling element bearings (REBs) are key components in rotating machines. 40% of the failures in electrical motors occur due to bearing faults (Sharma, Abed, Sutton, and Subudhi, 2015). Consequently, monitoring the health stage and estimating the remaining useful life (RUL) of the REBs is essential. Additionally, maintenance of rotating machines can be scheduled based on the RUL estimation, which will mitigate potential time wasting, economic losses and hazards (Wen, Rahman, Xu, and Tseng, 2022).

Research on methodologies for estimating the remaining useful life of REBs primarily falls into three categories: (a) methods driven by artificial intelligence (Ma, Yan, Wang, and Liao, 2023), (b) statistical approaches (Lim & Mba, 2015), and (c) physics model-based methodologies (Gabrielli, Battarra, Mucchi, and Dalpiaz, 2024). The authors' research will focus on the integration of statistical methods, such as the Kalman Filter (KF) and its variants, with physics model-based approaches, e.g., lumped mass models, to enhance the interpretability of RUL estimations under steady and varying operating conditions. However, current research may overlook several considerations in practical applications, including:

(1) Health indicators (HIs) directly affect the accuracy of RUL estimation. Therefore, they should reflect the degradation trend. There are the following issues regarding the HIs: (a) Current research mainly focuses on vibration signal analysis based on the cyclostationarity of REBs. The cyclostationarity of REBs is successfully applied for fault detection and fault diagnosis of REBs, obtaining exciting effectiveness based on the comparison between healthy cases and fault cases (Antoni, Xin, and Hamzaoui, 2017). However, prognostics necessitates indicators that are linked with the size of the defect which theoretically increases with the passage of time; (b) Few researchers pay attention to the physics models for the prognostics of the RUL because the crack inside the REBs cannot be directly observed. On the one hand, the signal acquired from sensors can deliver part degradation information, e.g., the vibration amplitude will increase as the defect extends intuitively. On the other hand, fluctuation can appear because of the operation condition changes, the complexity of the REBs' structure and the stochasticity of the degradation. So, how to connect the observable vibration data and the unobservable crack size, which will improve the accuracy and interpretability of prognostics, is a potentially interesting topic.

(2) In the degradation process of REBs, anomaly thresholds and failure thresholds are required to be determined which are key parameters for RUL estimation. The Anomaly thresholds determine when the RUL estimation should start, i.e., the end of the health stage (design life of components). The failure thresholds are required for the RUL calculation. They are points at which a component is not allowed to continue to serve. However, these two thresholds are difficult to be determined in real cases.

(3) Due to the nonlinearity of the degradation, the accuracy and stability of KF and its variants are problematic. For instance, the Extended Kalman Filter (EKF) uses the first derivatives to linearize the state and measurement functions to approximate the posterior probability. Consequently, a poor approximation may be obtained.

(4) Online RUL estimation should be highlighted because of the definition of prognostics. From the practicability perspective, methodologies should be able to estimate the RUL at the current time based on historical data. If a methodology requests the whole data to estimate the RUL of REBs, then it would be difficult to implement it in the industry.

(5) The uncertainty determination. The uncertainty of the estimated RUL is a key factor for the maintenance schedule. For the state estimation methodologies, specifically for the KF and its variants, what can be directly obtained is the approximation of the posterior probability distributions. This has to be clarified because some literature may directly use these distributions as the estimated RUL uncertainty. So, one issue is how to calculate the RUL uncertainty via the distribution of the estimated parameters.

(6) Besides the abovementioned issues, most of the research works focus on the information obtained from accelerometers but ignore other factors, for instance, temperature. So, how to combine different information obtained from different sensors (e.g., temperature sensors, strain gauges and fibres, etc.) is an interesting but challenging topic.

The authors' research aims to propose a methodology to estimate the RUL of REBs and validate it on degradation measurements. The following innovative contributions are expected to facilitate the development of PHM, especially for the prognostics of REBs:

(1) A generalized, robust and visualized RUL estimation methodology is expected to be delivered to the real industry.

(2) A series of datasets is expected to be published to facilitate PHM development.

(3) Some innovations regarding signal processing and RUL estimation are expected to be referenced for condition monitoring.

To achieve the goal and contributions mentioned above, a detailed research plan was proposed as follows and it is also summarized at a flowchart in Figure **1**.

(1) Literature review. Systematically review recent research on prognostics of REBs from 3 aspects: (a) State-of-the-art signal processing methodologies and HIs; (b) Different state estimation methodologies implemented for RUL prognostics of REBs. (c) Physical modelling of REBs. Issues existing in recent research will be summarized. In addition, the advantages and disadvantages of different approaches will be studied, which will be the foundation of future research.

(2) Study of HIs. This part mainly focuses on the state-of-the-art of signal processing methodologies which includes time, frequency and time-frequency analysis, especially for REBs whose vibration signal is a typical cyclostationary one. Firstly, an in-depth study on the cyclostationarity will be conducted. The HIs study will start from the Cyclic Spectral Correlation & Coherence (CSC) as it is one of the most versatile methodologies in anomaly detection and fault diagnostics of REBs, where the impulsiveness components can be demonstrated in a bi-spectral map based on the correlation between different frequency components at various cyclic frequencies (Antoni et al., 2017). The authors will further explore the CSC map and related carrier frequency band selection methodologies (for demodulation) to (a) obtain a full understanding of the vibration of REBs; (b) study typical HIs in time, frequency and time-frequency domain; (c) evaluate the potential CSC-based HIs for the next steps. Secondly, physical models, such as lumped mass models, will be further studied based on the current research.

(3) Selection of thresholds of the HIs: Two important thresholds, i.e., the anomaly threshold and the failure threshold, will be discussed in future research based on the HIs obtained in the previous step. For the anomaly one, current research mainly focuses on the impulsiveness of the signal in the time domain. The main task is finding a threshold where the fault can be detected as early as possible and outliers should be avoided simultaneously. CSC-based HIs are a potential approach as CSC is proven to be able to extract fault frequency components in very weak signals. Therefore, the authors will focus on how to balance the weak fault signal detection and the outliers caused by the environmental noise. For the failure threshold, the authors plans to explore different approaches, specifically including (a) fixed thresholds; and (b) dynamic thresholds. Fixed thresholds assume that for a specific kind of REBs, the failure points of the HIs should be the same. This kind of determination method needs a lot of measurements. In contrast, dynamic thresholds consider individual cases while ignoring the type of REBs. The core idea is setting a threshold based on historical data, which is more pragmatic in real applications. Therefore, the authors will focus on the latter one.

(4) State estimation techniques for prognostics. For the strategies of state estimation, the authors will explore different state-of-the-art technologies, e.g., KF and its variants, Gaussian Process (GP) and Wiener process models, etc. Specifically, the KF and its variants, as one of the most commonly used approaches will be emphasized. Besides, functions that describe the degradation trends will be studied. There are some ideas on the functions as follows: (a) One direction is creating a library of functions and adopting some specific strategies to switch from one to another during the degradation process of REBs, which assumes the degradation process can be divided into several stages, e.g., healthy stage, crack

initiation stage, crack propagation stage and fracture stage, where different stages have different features and consequently follow different functions; (b) Another direction is creating a function which can represent the full degradation stage, for instance, the Paris-Erdogan equation can follow the crack growth rate. These two directions will be considered and further studied.

(5) Uncertainty quantification: The uncertainty quantification will be studied. The uncertainty involves (a) the measurement errors and (b) the state functions errors. These two errors need systematic work to be determined. Monte-Carlo is one of the potential solutions. Besides, in practice, a decreasing uncertainty will be expected as time goes on because more historical data will have been obtained. So, exploring how to achieve an adaptive uncertainty approximation is also within the research plan.

(6) The last step will be the validation of the expected methodologies on accelerated degradation measurements using different sensors including accelerometers, microphones, strain gauges, optical fibers, temperature sensors, etc. Besides, different operational campaigns are planned to be conducted, e.g., constant speed and load and varying speed and load.

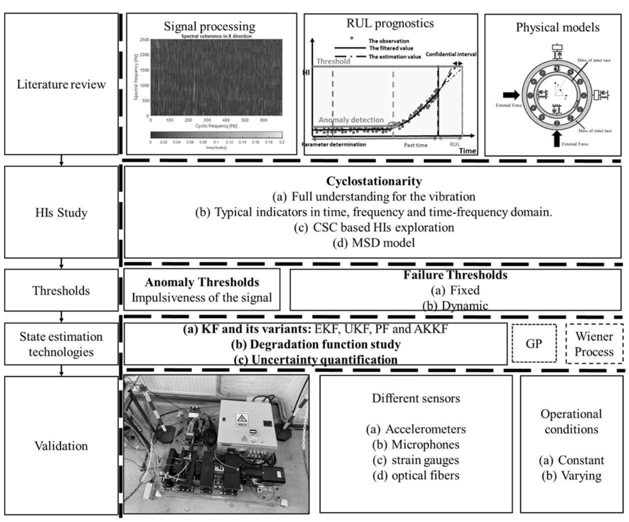

Figure 1. The flowchart of the research plan

Some work has already been realised. While some tasks are still going on, preliminary results can be reported in this abstract as follows. These findings will be studied further.

(1) The initial literature review has been finished and still open issues existing in recent research have been concluded. However, it should be noted that high-quality research is continuously published, so literature reading and corresponding improvements for the authors' research will also be made.

(2) HIs study is still going on. Some typical indicators have been studied. For instance, Squared Envelope Spectrum (SES) and CSC-based Improved Envelop Spectrum (IES) have been explored and a fault has been successfully categorized. As shown in Figure 2, the signals of a dataset were analyzed to identify the faults, using the Fourier Spectrum of the raw signal, the Squared Envelope Spectrum (SES) and the Improved Envelope Spectrum via Feature Optimisation-gram (IESFOgram) (Mauricio & Gryllias, 2021). It can be seen that SES and IES present a peak around 228.8 Hz which is close to the nominal BPFI, indicating the presence of an inner-race fault. In addition, for the lumped mass models, a model of a defective bearing has been built, where defects are described by extended angles and depth parameters, as shown in Figure 3. Figure 4 presents a simulated signal where a specific depth and extended angle are assigned. By assigning different combinations of depths and extended angles, an RMS-map can be obtained as shown in Figure 5, where the connection between the size of the defects and the corresponding vibration RMS, which can represent the vibration energy, is found. The next step is to find a strategy to extract a defect-size-based indicator, where the defect size should be increasing as time evolves. Then combined with the previous fault detection technology (SES, IES), a methodology will be developed. This part is still going on.

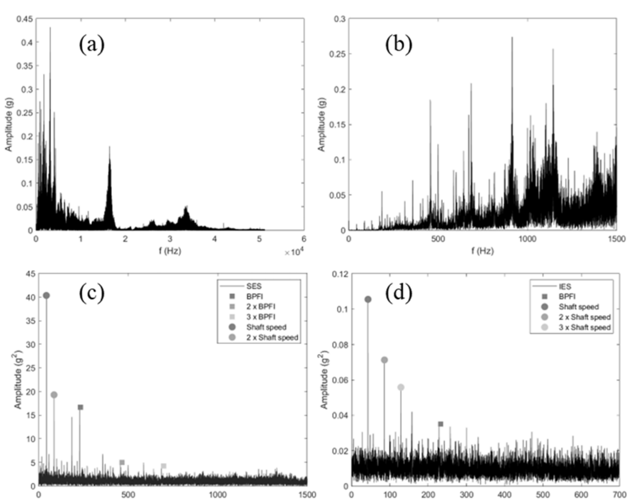

Figure 2. Spectra of the vibration signal. (a) Single-Sided Amplitude Spectrum, (b) Zoomed view of (a) up to 1500 Hz, (c) Squared Envelope Spectrum (SES) and (d) Improved Envelope Spectrum (IES)

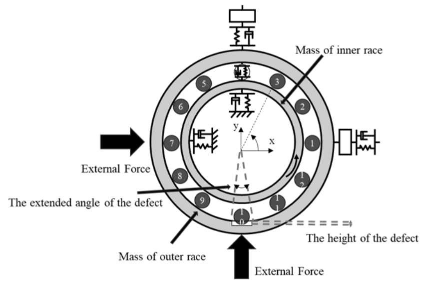

Figure 3. A lumped mass model of a defective bearing

(3) An innovative framework was proposed regarding the nonlinearity problem mentioned in previous sections. As shown in Figure **6**, the framework is based on typical HIs (e.g., RMS) and the Adaptive Kernel Kalman filter (AKKF). A kernel mean embedding (KME) and the kernel Kalman rule (KKR) were implemented to approximate the posterior probability in a nonlinear dynamic system, where better results were obtained compared with the EKF. As shown in Figure 7, M1 and M2 are single exponential functions and double exponential functions, respectively. It can be found that the AKKF shows superior results as the estimated RUL is closer to the actual life.

(4) Measurement campaigns in a dedicated bearing diagnostics test rig are taking place and will be used for the development, testing and evaluation of the diagnostic framework.

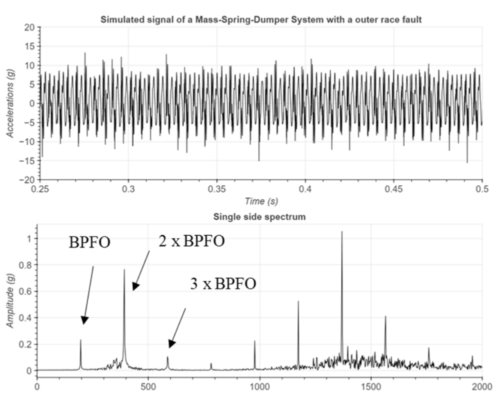

Figure 4. The simulated vibration signal

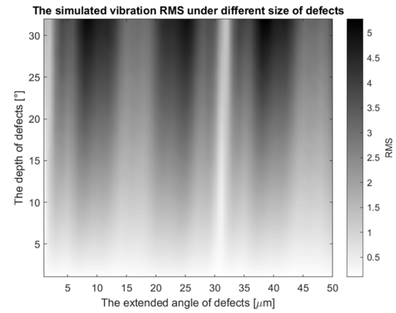

Figure 5. The simulated vibration RMS under different size of defects

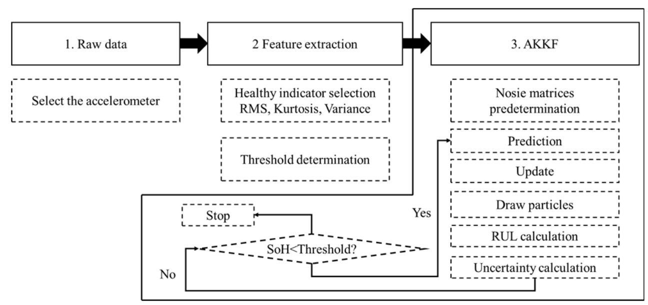

Figure 6. A framework of RUL estimation based on AKKF

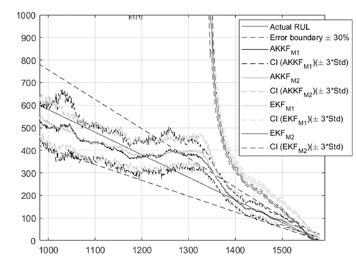

Figure 7. A comparison of estimated RUL between EKF-based model and AKKF-based model.

In conclusion, the authors summarized some issues in current research. A series of preliminary explorations have been performed and some results have been already obtained. Finally, a systematic methodology is expected to be proposed by combining all the abovementioned research to facilitate the development of the PHM.

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BIOGRAPHIES

Zhen Li received his Bachelor of Engineering degree in Engineering Mechanics from Northwestern Polytechnical University, China and his Master of Engineering degree in Solid Mechanics from Northwestern Polytechnical University, China. He joined the Noise and Vibration Research Group in the Department of Mechanical Engineering at KU Leuven, Belgium, as a PhD researcher in 2022. His research interests lie in the areas of remaining useful life prognostics of rotating machine using state estimation technologies.

Konstantinos Gryllias received the Diploma and Ph.D. degrees in mechanical engineering from the National Technical University of Athens, Athens, Greece, in 2004 and 2010, respectively. He is currently a Professor of vibro-acoustics of machines and transportation systems with the Department of Mechanical Engineering, KU Leuven, Leuven, Belgium. He also serves as the Manager of the University Core Lab Flanders Make@KU Leuven Motion Products, Belgium. His research interests include condition monitoring, signal processing, prognostics, and health management of mechanical and mechatronic systems.