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Notification No: 542/2023
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Date of Award: 14-06-2023
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Topic of Research: **Some Studies on Fault Detection in Engineering System**

FINDINGS

There is an ever-increasing demand to ensure consistent performance of the present-day engineering systems due to their increased complexity. The emergence of the faults deteriorates the performance, and their timely detection is essential not only to ensure an uninterrupted operation of the system but also to prevent any catastrophic failure. The present research work is focused on developing novel mathematical models for fault detection of the most critical and indispensable component of an engineering system i.e., the rolling element bearing, using vibration signal, used as the most viable method amongst the available techniques. The development of a novel mathematical model based on vibration signatures requires in-depth understanding of the various sources and characteristics of vibration signals emanating from healthy and defective bearing. The existing mathematical models lack a quantitative assessment of varying compliance vibration and its possible implications on early-stage fault diagnosis. The available models on extended spalls, and their propagation, are also not very efficient. Further, the automated fault diagnosis using machine learning techniques are increasingly becoming popular but possess limited effectiveness due to improper selection of the fault features, which yield satisfactory results only in limited cases, like those for artificial faults, and disregard the naturally evolving bearing faults.

In order to overcome the aforementioned limitations, the present research study was conducted with the primary objective of improving the existing methods for bearing fault diagnosis. To achieve this, four main objectives were framed. The first two objectives address the issues of localized and extended spalls by developing improved theoretical models for simulating the response of a ball bearing with localized and extended outer race defects. The third objective aims at formulating a new theoretical model to investigate the effects of various parameters on the growth of localized as well as extended spalls under possible conditions of ball-raceway impacts. Finally, the fourth objective attempts to build a novel automated fault diagnosis framework based on machine learning, by using a new combination of fault features, which is capable of diagnosing both artificial and natural spalls with reasonably high accuracy, and good performances.

The proposed theoretical models on localized and extended spalls were formulated by incorporating time varying behaviors of contact stiffness, localized Hertzian deflection, squeezed film damping, and non-linear forces at ball raceway contacts. Additionally, the expressions of time dependent ball sink inside the spall were derived while considering the localized deformation and dynamic nature of other contact parameters. The proposed models were validated using experimental results for which a dedicated experimental test rig was designed and developed using a systematic procedure. The emphasis in the first model lies on investigating the varying compliance vibration. The in-depth analysis led to the finding that the existence of outer raceway defect peaks due to varying compliance may build a misleading impression of a defect even for healthy bearing. Hence, fault identification and defect size estimation carried out directly on the ground of these impulses without a prior knowledge of their actual cause, could result in non-optimal decisions.

In the second model, the focus lies on precise fault quantification of extended outer race defect. The impulse force train due to impacts near the entry and the exit edges are modelled and studied along with other important dynamic characteristics of the rotor bearing system under different operating conditions and defect parameters. Defects of five different sizes were diagnosed from the experimental data, in light of the proposed method. The theoretical results were successfully validated using experimental observations, with a very good resemblance between the actual and the estimated defect sizes, with a maximum error of only 4.88%, corresponding to the smallest defect.

The third model is intended to simulate the dynamic impact force, and the resulting localized deformation and non-linear, concentrated stress to obtain a glimpse of the tendency for development of crack and its propagation in the most stressed zones of the spalls. The growth parameters were evaluated for both localized and extended outer race faults under two possible cases of ball impact, termed as 'Impact Under Compression (IUC)' and 'Free Impact (FI)'. The simulation results revealed that both the radial load and speed favor spall propagation in case of IUC, whereas it remains unaffected by the radial load in FI condition and exhibits non-monotonous behavior with increasing speed. Moreover, the defect geometry has a mixed influence on the behavior of the defect growth parameters.

Finally, to achieve the fourth objective, a new combination of fault descriptors, including the Hjorth's parameters, and a few other statistical features was proposed, and its effectiveness analyzed on classification performances of k-Nearest Neighbor (k-NN) and Support Vector Machine (SVM). For this, the spalls belonging to both the artificial and natural types were used from three different repositories. The proposed framework improved the accuracies of fault prediction as compared to the previously reported algorithms. The maximum accuracies between 99.3% to 99.6% were achieved for artificial fault whereas that between 91.3% to 99.9% for natural spalls. Beside accuracy, the precision, recall, and F1-score were also enhanced using the proposed combinatory features.

The detailed theoretical modeling and experimental investigations carried out in the present research work culminating in improved mathematical models will certainly enhance the systematic understanding in the field of bearing fault diagnosis. The research findings will eventually be helpful in building an effective diagnosis strategy.