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Ball bearing defect models: A study of simulated and experimental fault signatures

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ABSTRACT

Numerical model based virtual prototype of a system can serve as a tool to generate huge amount of data which replace the dependence on expensive and often difficult to conduct experiments. However, the model must be accurate enough to substitute the experiments. The abstraction level and details considered during model development depend on the purpose for which simulated data should be generated. This article concerns development of simulation models for deep groove ball bearings which are used in a variety of rotating machinery. The purpose of the model is to generate vibration signatures which usually contain features of bearing defects. Three different models with increasing level-of-complexity are considered: a bearing kinematics based planar motion block diagram model developed in MATLAB Simulink which does not explicitly consider cage and traction dynamics, a planar motion model with cage, traction and contact dynamics developed using multi-energy domain bond graph formalism in SYMBOLS software, and a detailed spatial multi-body dynamics model with complex contact and traction mechanics developed using ADAMS software. Experiments are conducted using Spectra Quest machine fault simulator with different prefabricated faulted bearings. The frequency domain characteristics of simulated and experimental vibration signals for different bearing faults are compared and conclusions are drawn regarding usefulness of the developed models.

1. Introduction

Prompt detection of any incipient fault of in a critical component is important to avoid machine breakdown. Rolling element bearings are critical components in many rotating machineries. In these machines, vibration analysis is often used for condition monitoring of rolling element bearings. The bearing characteristics frequencies (BCFs) provide a theoretical estimation of frequency to be expected in the frequency spectra when there is any defect on parts of rolling element bearing. This assumes that an ideal impulse occurs when a rolling element strikes a fault-induced discontinuity on its rolling path. Depending upon the design parameters, many theoretical models of vibration generation mechanism are available. In the simplest form, kinematics based simplifications are employed to find the BCFs, which are functions of bearing geometric parameters, number of rolling elements and frequencies of inner race and outer races. However, the vibration signal collected from the bearing system is contaminated by external noise, structural vibrations and external disturbances. The signal is therefore treated through many signal processing steps to remove noise and finally a diagnosis

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scheme (post processing step) is applied to characterise the frequency components in the vibration signal.

Often, the contact between rolling element and bearing races is discontinuous, and simple models based on continuous traction (no-slip) do not reproduce same qualitative vibration signal as that in a real industrial application. Likewise, models which do not explicitly model cage motion fail to replicate critical phenomena like bearing seizure. A model needs to be accurate enough to substitute experiments. The biggest advantage of having an accurate model is the ability to simulate various combinations of fault scenarios and generate corresponding responses, using which a knowledge-base can be generated to link various fault symptoms to their causes and finally, a root cause analysis system can be designed.

There is a lot of work reported on diagnosis of faults in rolling element bearings using vibration analysis [1,2]. The vibration signatures used for analysis may be experimental or generated through simulation of appropriate models. Some important diagnosis schemes for diagnosis of rolling element bearings are high frequency resonance technique or envelope analysis [3,4], time synchronous averaging [5], spectral kurtosis [6], higher order spectral technique [7], wavelet analysis [8–10] and empirical mode decomposition [11].

The dynamics of rolling element bearing is affected by different operational and design parameters. However, it is almost impossible to replicate these parameters in an experimental study. So, a numerical model can be used to predict the behaviour of rolling element bearing under different parameters. The dynamic interaction of different parts, traction forces, slip and lubrication effects are generally considered while developing a mathematical model of a bearing. These models can be broadly divided into two types, i.e. quasi-static model and dynamic model [12]. In a quasi-static model, the force and moment equilibrium equations are considered whereas in a dynamic model, the differential equations of motion of each part of the rolling element bearing are considered. The dynamic model provides a time-domain transient simulation of the response of different parts of the bearing. Many works have been reported on the dynamic modelling of rolling element bearings [13]. Some important contributions in modelling of rolling element bearing dynamics pertain to formulations of differential equations of motion [14,15], defect geometry modelling and evolution [16], and multi-body dynamics model [17,18].

There are many commercially available computer codes and multi-body dynamics simulation software which can be used to model rolling element bearings. Some difficult analyses like dynamic analysis of cage behaviour in tapered roller bearing [19] and dynamic behaviour and resonance characteristics analysis [20] are reported using multi-body simulation (MBS) software ADAMS. Some of the commercial software dedicated towards dynamic analysis of rolling element bearings are BASDAP [14], SHABERTH [21], COBRA [22], DREB [23], ADORE [12], BEAST [16], CYBEAN [24] and CAGEDYN [25]. However, these specialized software are confined to only rolling element bearing analysis and cannot be coupled to models of machines or complex rotor systems as easily as can be done with MBS software. Rolling element bearing model, developed using multi-body system approach and vector bond graph form, where each rolling element, inner and outer races are modelled as six degrees of freedom system, is reported in [26]. The effects due to contact deflection forces, traction, gyroscopic and centrifugal forces, slip, contact separation, and localized fault were taken into consideration in that model whereas the effects due to cage dynamics was neglected. A model of rolling element bearing using planar multi-body dynamics formulation and bond graph approach is reported in [27], where the effects due to preload, unbalance, traction and cage dynamics are taken into consideration.

In this paper, three different models of ball bearing with increasing complexity and computational requirements are presented. The first is a 5-DOF model which is based on an earlier reported work in [28] and is implemented in MATLAB-Simulink environment. This model considers the effects due to preload and normal force due to ball race contact and neglects the effects due to traction forces. The second model is a more advance model based on an earlier reported work of these authors in [27] where multi-body dynamics approach is used to create a bond graph [29–32] model of rolling element bearing. In addition to normal force and preload as in earlier model, the effects due to slip, cage dynamics and inertia of cage and ball are taken into consideration while developing the model. In those two works, the models of rolling element bearing are two-dimensional and only consider the dynamics of test bearing, whereas a rolling element bearing test rig consists of two or more bearings and a rotor shaft with few rotor disks. Thus, the third model of deep groove ball bearing with rotor shaft and disk is developed using 3-D multibody simulation (MBS) software ADAMS. These three models are used to extract the frequency domain features of a ball bearing in presence of different imperfections in its important parts. The ability of the developed models to reproduce similar frequency domain features under various bearing faults is evaluated by comparing the results with those obtained from experiments.

Before developing the models of deep groove ball bearing with various faults, the general layout of the experimental test rig is discussed in Section 2. Sections 3, 4 and 5, respectively, explain the 5-DOF Simulink model, bond graph model and ADAMS model of the system. Section 6 details the signal processing steps and the frequency domain fault diagnosis scheme used in this article. A comparative performance evaluation of the developed models under different fault scenarios is carried out in Section 7. Final conclusions and perspectives are drawn in Section 8.

2. Experimental setup

The machine fault simulator (MFS) developed by Spectra Quest, shown in Fig. 1, is used to perform the experiments. It consists of an induction motor (Marathon, 3-phase, ½ HP), two aluminium pedestals, a loader, a coupling (Lovejoy), two ball bearings (1′′ MB-ER-16K, Rexnord) and a variable frequency drive as its principal components.