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A semi-analytical bearing model considering outer race flexibility for model based bearing load monitoring

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ABSTRACT

This paper proposes a novel semi-analytical bearing model addressing flexibility of the bearing outer race structure. It furthermore presents the application of this model in a bearing load condition monitoring approach. The bearing model is developed as current computational low cost bearing models fail to provide an accurate description of the more and more common flexible size and weight optimized bearing designs due to their assumptions of rigidity. In the proposed bearing model raceway flexibility is described by the use of static deformation shapes. The excitation of the deformation shapes is calculated based on the modelled rolling element loads and a Fourier series based compliance approximation. The resulting model is computational low cost and provides an accurate description of the rolling element loads for flexible outer raceway structures. The latter is validated by a simulation-based comparison study with a well-established bearing simulation software tool. An experimental study finally shows the potential of the proposed model in a bearing load monitoring approach.

1. Introduction

Rolling bearings are commonly used machine elements permitting rotational motion of shafts. They are applied in a wide range of applications from simple commercial devices to highly complex mechanisms. As in many facets of mechanical engineering increasing demands are put on rolling bearings. Besides development in areas as for instance lubrication, sealing and fatigue life, special interest lies in lifetime prediction and fault detection in order to avoid unnecessary upkeep and breakdowns. This latter is of utmost importance as bearings are usually essential machinery components [1].

A wide variety of damage modes might cause premature bearing failure. Examples are numerous and include manufacturing errors, excessive or improper loading, misalignment, overheating, corrosion and lubrication failure [2]. Next to premature failure modes a bearing will furthermore eventually fail in time due to fatigue of the bearing material. As bearing failure is one of the most common reasons for machinery breakdowns [3] bearing condition monitoring is an active field of research.

Incipient bearing failure is often characterized by a local defect on one of the bearing components and the detection of such defects is the main focus of condition monitoring [4]. Various approaches based on vibration, acoustic emission, sound pressure, lubrication and thermal analysis have been developed for detection and diagnosis of bearing defects [5–8]. Vibration analysis is the most common approach in both literature and industry and is based on various types on analysis in the

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vibration spectrum [9,10]. Advantages of these approaches relate to the basic sensory equipment needed, their effectiveness and the ability to detect the location of the defect [11,12]. Acoustic emission approaches have also been successfully applied and studies show that it allows for detection subsurface cracks before spalling occurs [13,14]. The approach itself however is considerably more extensive as sensor location is crucial and signal processing is more complex. In lubrication analysis on- or off-line debris detection is applied on the bearing lubricant [15]. Major benefit of this approach is the independence of background noise and machine operating conditions, however its drawbacks include processing complexity and classification. Thermal analysis based condition monitoring approaches [16,17] provide similar advantages and drawbacks. For improved fault diagnostics combinations of different approaches and analysis techniques can be applied [18,19].

Excessive or improper loading and bearing misalignment relate to a considerable portion of local defect initiation and growth. Continuous load monitoring could detect these damage modes and therefore help to avoid bearing failures. Next to that it could serve as a valuable control input for system control [20]. Load monitoring at the bearing level can be classified in deformation and displacement based approaches. The deformation based approaches are founded on strain measurement at the non-rotating bearing outer-ring by the use of strain gauges or optical fibres [21–26]. Displacement load monitoring approaches are based on the measurement of the relative displacement of inner- to outer ring by the use of hall effect, eddy-current or capacitive sensors [27–29]. In both load monitoring principles the measured physical quantities are translated to the bearing loading by empirical methods as least squares fitting [30,31] or artificial neural networks [32]. In the deformation based approach this last step however is extremely challenging as the relationship between measured strain and loading is highly non-linear [23]. To capture this non-linearity adequately a model based approach is preferred.

Modelling bearing behaviour for real-time load monitoring is a complex issue as an accurate description of the behaviour is desired whilst computing power is limited. Size and weight considerations during system and bearing development often results in flexible structures that deform considerably even at standard operational loads. This leads to altered load distributions, deflections, contact stresses and fatigue endurance compared to calculations using rigid assumptions. Considering the structural bearing deformation is thus of paramount importance for accurately describing bearing behaviour. Well established computational low cost analytical bearing models [1,33,34] are thus inapplicable due to their assumptions of rigidity. The usage of Finite Element Modelling [35], allowing for an accurate description of the flexibility, on the other hand is too computationally costly. Model reduction of for instance contact mechanics [36–38] or deformation behaviour [39] furthermore does not provide sufficient computational gain for real-time calculation. The most appropriate modelling approach for real-time load monitoring is therefore found in-between the analytical and Finite Element based approaches in the form of a semi-analytical flexible bearing model [40–42].

The semi-analytical flexible bearing models are formed by extension of traditional rigid analytical modelling by a semi-analytical description of the bearing outer-ring deformation. The in-plane deformation or ovalization of the outer-raceway is described using a Fourier series representation. The Fourier coefficients are either analytically derived from Timoshenko's theory [40–42] or determined based on a Finite Element Analysis of the structure [42]. Main limitation of the current modelling approaches is the assumption of axisymmetric geometries. This limits the applicability in real-life situations as bearing housings in general do not comply to this strict geometric limitation.

To accurately include the structural deformation of any outer-ring housing geometry at low computational cost in this paper a novel semi-analytical bearing model is proposed. By the use of static deformation shapes and a Fourier series based compliance approximation an accurate and efficient representation of the raceway flexibility is obtained. The Fourier coefficients are determined a priori by the use of a Finite Element study on the outer-race structure according to a simple procedure. Simulation studies show that the model is able to accurately describe the rolling element loads when significant structural bearing deformation is present. The model is furthermore implemented in an experimental study to show its potential in load monitoring.

2. Bearing model

In this Section the proposed bearing model is developed. The following important assumptions and simplifications are applied: (i) as low speeds are considered the effect of centrifugal forces is neglected, (ii) both friction and cage interaction forces are neglected as they are insignificant compared to the rolling element normal loads and (iii) only radial deformation of the outer race is considered as the axial component in general is considerably less excited and influential. Furthermore some minor assumptions are provided within the work itself.

2.1. Coordinate systems

For the development of the bearing model two coordinate systems are used, namely a Cartesian and cylindrical system. Fig. 1 shows the groove curvature loci of inner and outer raceway and their associated parameters in the Cartesian x, y, z space. The origin of the Cartesian space is located at the inner ring reference point at its undisplaced position. The x and y-axis are respectively the vertical and horizontal radial bearing direction whilst the z-axis is aligned with the bearing axis. All rigid body displacements and bearing loads are defined in this Cartesian system.