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Distributed bearing fault diagnosis based on vibration analysis

Boštjan Dolenc [a,b,*], Pavle Boškoski [a], Đani Juričić [a]

[a] Jožef Stefan Institute, Department of Systems and Control, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
[b] Jožef Stefan International Postgraduate School, Jamova cesta 39, SI-1000 Ljubljana, Slovenia

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ABSTRACT

Distributed bearing faults appear under various circumstances, for example due to electroerosion or the progression of localized faults. Bearings with distributed faults tend to generate more complex vibration patterns than those with localized faults. Despite the frequent occurrence of such faults, their diagnosis has attracted limited attention. This paper examines a method for the diagnosis of distributed bearing faults employing vibration analysis. The vibrational patterns generated are modeled by incorporating the geometrical imperfections of the bearing components. Comparing envelope spectra of vibration signals shows that one can distinguish between localized and distributed faults. Furthermore, a diagnostic procedure for the detection of distributed faults is proposed. This is evaluated on several bearings with naturally born distributed faults, which are compared with fault-free bearings and bearings with localized faults. It is shown experimentally that features extracted from vibrations in fault-free, localized and distributed fault conditions form clearly separable clusters, thus enabling diagnosis.

1. Introduction

Bearing faults are among the most common causes of failure in rotating machines [1,2]. The root cause of such failures include pitting, spalling, electroerosion, and wear. Most commonly, faults occur as surface damage on the bearings' raceways or on the rolling elements. Such surface defects can appear in two forms: localized faults or distributed faults. In this paper, an updated bearing model, capable of describing both distributed and localized bearing faults, is presented. Introducing imperfections in bearing components shows how some of these faults manifest in vibrations and differ from each other, thus enabling the segregation of localized and distributed faults.

The term “distributed fault” may appear somewhat confusing. Usually, distributed bearing faults are regarded as irregularities in bearing geometry that occur due to imperfect manufacturing, faulty mounting and misuse, not actual surface damage [3–6]. In this paper, distributed faults are regarded as bearing surface defects spread over a large area; two or more rolling elements can be located in the faulty area at a given moment.

The majority of published works that address bearing diagnostics focus solely on localized faults [7–10]. Although these faults indicate an emerging problem in a bearing, it does not necessarily mean that a faulty bearing is at the end of its lifetime and should be replaced [11]. As the bearing ages, localized faults evolve and spread over a wider area, thus becoming distributed and causing a distinctive vibration pattern. By monitoring the condition of a bearing, one can draw

* Corresponding author.
E-mail address: bostjan.dolenc@ijs.si (B. Dolenc).

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inferences about its remaining useful life [12,13]. Although fault size is a convenient condition indicator, published work on the analysis of vibrational patterns, produced by bearings with distributed faults is rather scarce.

An approach towards estimating the size of a fault is based on the time difference between the moments when the rolling element enters and exits the damaged area [14,15]. Though both methods estimate fault size, their main focus are smaller, localized faults. Al-Ghamda and Mba [12] studied the effect of fault size on RMS and kurtosis of acoustic emissions (AEs) and vibration signals. The faults considered were somewhat larger (i.e. a few millimeter s wide) than those in previously presented work. Eftekharnejad et al. [16] studied the effect of a growing defect on the envelope spectrum while monitoring vibrations and AEs. Although the authors investigated the envelope spectra of excited vibrations and AEs, the focus of the research was the comparison of the two condition variables. Sawalhi and Randall [17,18] presented a combined dynamic model for gears and bearings that is also capable of describing distributed faults. Vibrations of measured and simulated extended faults were compared by means of the envelope spectrum and spectral correlation function. The results showed that extended faults could be detected using vibration analysis; however, no rule for distinguishing between localized and extended faults was provided. de Castelbajac et al. [19] studied the effect of distributed faults on high spindle bearings. They introduced a new spindle bearing noise criterion, where statistical the properties of the frequency spectrum of vibrational signals were investigated for condition monitoring.

To sum up, previous work mainly focused on analysing vibrations generated by small faults (in the range of a few millimeters at most), whereas the faults considered in this research are a few times larger. Some of the methods presented were successful at fault size estimation, but only a few of them considered naturally evolved faults. Moreover, surface defects were mostly seeded on the race surface, ignoring the possibility of multiple damaged areas.

The purpose of this paper is to determine the effect of a distributed fault on the envelope spectrum of a vibrational signal. By upgrading the model developed by Sawalhi and Randall [17], it is possible to show that distributed bearing faults can be distinguished from localized ones by introducing the imperfections of the bearing elements into the model. The simulated results are validated using vibration patterns generated by bearings with naturally born distributed faults spread over larger portions of their circumferences.

2. Modeling the vibrational response of a faulty bearing

During operation, bearings are subjected to forces that excite system eigenfrequencies. Due to waviness in the bearing races and rollers, even fault-free bearings generate some vibrations. However, distinct vibrational patterns occur when surface damage appears on one of the bearing elements.

When a rolling element hits a localized damaged spot, it excites impulse response $s(t)$. Due to rotation, the responses form a train of impulses and produce s vibrational pattern, which can be written as [20]

$$y(t) = \sum_{i=-\infty}^{i=\infty} A_i s(t-\tau_i) + n(t), \tag{1}$$

where A_i indicates random amplitudes, τ_i stands for random impact moments and $n(t)$ is additive noise. Signal $y(t)$ accurately describes the vibrational response of a bearing with a small-sized localized fault.

Although this model can be used to simulate any type of bearing fault with properly defined random variables A_i and τ_i, their characterization is a formidable task. Moreover, as the bearing ages, multiple damaged areas develop, resulting in a more complex vibrational pattern.

2.1. Bearing vibration model

To simulate a bearing vibration response, a vast variety of models are available. The model proposed by Sawalhi and Randall [17,18] sufficiently describes all of the crucial dynamic properties of a bearing mounted in motor housing.

The five DOF (degrees of freedom) model, shown in Fig. 1, omits the mass and inertia of the rolling elements. Two DOF describe bearings' inner race or shaft displacement (x_s, y_s), while (x_p, y_p) describe the motion of the bearing housing where the outer race is mounted. The fifth DOF describes a high frequency response of the bearing y_b, where the vibrations are measured. $k_p, c_p, k_s, c_s, k_r, c_r$ are the stiffness and damping coefficients of the shaft, housing and bearing. k_b is the bearing load deflection factor.

Through Hertzian theory, the model describes contact forces between bearing elements that generate vibrations. Elastic deformation δ_j of the jth rolling element is a function of the inner race displacement relative to the outer race, the rolling element position in time ϕ_j, clearance c and surface defect $C(\phi)$, which can be incorporated in elastic deformation. The overall contact deformation for each rolling element is calculated as follows:

$$\delta_j = (x_s - x_p)\cos\phi_j + (y_s - y_p)\sin\phi_j - \\ - c - \beta_j C(\phi) \tag{2}$$