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Fault detection and isolation of bearings in a drive reducer of a hot steel rolling mill

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ABSTRACT

Defective bearings are a major concern in rotating machinery. In this work we propose a two-step scheme, relying on two complementary data-driven techniques, for fault detection and isolation for a drive reducer in a hot steel rolling mill. A preliminary fault detection phase is based on a computationally lightweight time-domain multivariate statistical technique. Secondly, a more computationally intensive frequency-domain analysis method is used to confirm the fault detection and provide information on its frequency characteristics. Automatic procedures are sketched for the application of both techniques. Bearing defect models are employed to test their fault detection and isolation capabilities.

1. Introduction

In plants involving rotating machinery, defects in bearings can crucially affect the process quality (Randall, 2011). For this reason, the early and automatized identification of faulty bearing conditions is of great importance in industrial practice (Ericsson et al., 2005), fostering research in fault detection and isolation.

Fault detection methods can be roughly classified into two wide categories: model-based methods and data-driven (also denoted history-based) methods. The former require the availability of a physical model of the system under analysis, the derivation of which is a complex and time consuming task in the case when the dynamics of bearings is concerned. Data-driven methods are quite popular in the literature (see, *e.g.*, Randall, 2011; Zhang et al., 2011) because they do not require any specific *a priori* knowledge on the system characteristics and only rely on the processing of available data measurements and statistical techniques. A great variety of methods falling in the latter category have been proposed in the literature, ranging from time-domain to frequency-domain techniques, including mixed time–frequency methods.

In this work we propose a two-step scheme, relying on complementary data-driven techniques, for fault detection and isolation for a drive reducer in a hot steel rolling mill. Specifically, a preliminary fault detection phase is carried out based on a simple and computationally lightweight time-domain analysis algorithm. Secondly, a more complex and computationally intensive method is proposed, based on frequency-domain analysis, targeting a more precise identification of the fault characteristics. Although there are several measurable system variables that can provide information on an incipient bearing fault (*e.g.*, temperature, vibration and acoustic noise), both the proposed procedures essentially require vibration measurements solely. These signals are easily collected during system operation in the considered test rig.

The preliminary fault detection method uses Statistical Process Control (SPC) techniques based on Hotelling's T^2 distance (Montgomery, 2009), computed from the available vibration signals. SPC is a classical statistical methodology for monitoring the process operation and assess if nominal safety conditions are preserved. More precisely, multivariate statistical analysis is used to define a multi-dimensional confidence region for a set of process-related variables, which can then be used to determine if the considered set of variables remains in the safe region. Multivariate statistical techniques are extremely appealing to their simplicity, and are often employed for process monitoring, fault detection and diagnostic tasks on process plants, and specifically for the detection of gearbox defects (Baydar, Chen, Ball, & Kruger, 2001; Ge, Kruger, Lamont, Xie, & Song, 2010) A completely automatized procedure is proposed to process the raw signals and perform the fault detection. Briefly, several vibration signals are first collected performing different experiments on the test rig in normal operating conditions. Signal portions characterized by sufficient signal level and quasi-stationarity are isolated in the raw data. Then, these signal portions are further divided into subsequent short data blocks, each of which is synthetically characterized by a set of aggregate features. A reference model is formed based on this aggregate characterization of

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the vibration signals. Faulty conditions are finally identified by monitoring if the data collected during normal plant operation display significant deviations (in a statistical sense) from the reference model.

Since multivariate analysis does not provide any additional information regarding the cause or location of the detected bearing fault, the subsequent step aims to identify the frequency at which a fault occurs and the type of fault, such as ball or cage damage or inner/outer race defect. Fault frequencies are particularly important for fault isolation, since direct correspondences between specific faults and their characteristic frequencies are *a priori* known (Randall, 2011). This motivates the introduction of a second frequency-domain procedure to complement the outcome of the time-domain one described above. Notice that standard spectral analysis is not particularly effective in this case, since the amplitude of the impulsive type signals associated to defects of the bearings is typically much smaller than that of the signal measured in the absence of fault. Thus, it becomes necessary to employ specific frequency domain techniques that enable to discriminate the contributions associated to faults from the characteristic frequencies of the system in the spectra of the vibration signal. For this purpose, one can resort to the envelope analysis, a well-established technique, see Randall and Antoni (2011), widely employed in the diagnosis of rotation machines. This analysis requires first that the data be appropriately filtered to emphasize the fault with respect to other components, so as to facilitate the fault detection. The design of such filter is here based on the analysis of the spectral kurtosis (Randall & Antoni, 2006; Sawalhi & Randall, 2004). Another automatized procedure has been developed to process the measured signals using the explained envelope analysis. Since this procedure is computationally much more intensive than the previous one based on multivariate analysis, it provides a complementary tool, which can be employed when the former suggests the possibility of a fault, with the aim of providing further evidence and details on the fault.

A major improvement to standard envelope analysis is here introduced, to cope with the case of time-varying shaft speed typically encountered in applications as the one considered. Indeed, since fault frequencies are linearly related to the shaft angular frequency, the variability of the shaft speed blurs the periodic pattern associated to the defect, complicating its detection. For this reason, we here operate on vibration signals represented as a function of the motor shaft angle rather than of time, since in the "angle domain" the fault periodicity can be clearly detected. The two fault detection procedures have been tested using several real data measurements obtained during actual plant operation and simulating the insurgence of defects using standard bearing defect models. The sensitivity of the procedures has been analyzed with respect to amplitude and frequency of the faults. It is shown that the proposed approach (i) can be effective in detecting and isolating incipient local faults at an early stage and (ii) in view of its robustness and reliability features, it is particularly suitable for industrial deployment.

The rest of the paper is structured as follows. The test rig is described in Section 2, together with the measurement system. Section 3 illustrates the first procedure, based on condition monitoring for the detection of bearing-related faults, while Section 4 describes the second procedure, which employs envelope analysis for the frequency-domain characterization of a detected fault. Finally, Section 5 illustrates the application of the presented procedures.

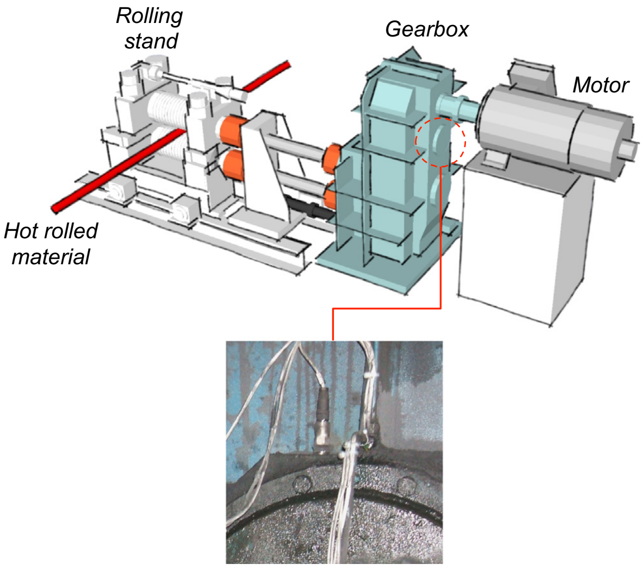

Fig. 1. 3D rendering of the reversible blooming mill to be studied and actual image of the accelerometer.

2. Device description and problem setting

2.1. The drive reducer

The system to be studied consists of a gear reducer serving a reversible blooming mill, represented in Fig. 1.

The hot steel is rolled in multiple runs between the stand's rolling rolls, and at each run the rolled section is reduced and the bar elongates. The turning direction of the cinematic chain is inverted at each run through a deceleration, stop, inversion and acceleration sequence. Seven accelerometers have been installed on the gear reducer to sense the vibration signals on a target group of bearings. The described gearbox application is one of the countless arrangements that can be found in rolling mills. A data-driven approach is more suitable to master this complexity, the development of a physical model for each drive arrangement's typology being impractical and anti-economic. As additional benefit, the proposed statistical approach offers a unique fingerprint of the gearbox under observation not replicable with even the most sophisticated physical model.

The objective is to identify any abnormal operating condition of the bearings and possibly isolate the faulty element. Such analysis will be performed using batches of data corresponding to the 4 runs of each steel bar. Note that this does not imply a strong performance limitation compared to real-time analysis, since the bearing degradation is a slow process compared to the duration of each individual batch processing (which typically takes less than a minute).

2.2. Available signals and data features

The available measurements are:

- Seven vibration signals measured by seven accelerometers attached to the shell of the drive reducer. Each accelerometer is placed in the proximity of a bearing, so that it can be assumed that each vibration signal has an essentially one-to-one correspondence with a specific bearing.
- The current absorbed by the motor driving the mill.
- The angular velocity of the motor.

An example of typical vibration and current signals measured in the described plant is reported in Fig. 2.

Several data sets have been recorded in nominal conditions (with no bearing defects detected), accounting for different process runs (bars can have slightly different size and steel quality).

A preliminary frequency analysis (see Fig. 3) reveals several sharp peaks in the amplitude spectra (*e.g.* at 300 Hz, and occasionally at the