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A torque-based method for the study of roller bearing degradation under poor lubrication conditions in a lead–bismuth environment

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HIGHLIGHTS

- An original study of roller bearings in lead–bismuth.
- Bearing friction torque history improves post-test diagnosis.
- Torque signal provides complementary information in different domains.
- There is a basis for live condition monitoring with additional research.

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ABSTRACT

The bearing is a critical and complex component of the in-vessel fuel manipulator in the future MYRRHA nuclear research reactor. All components are fully submerged in the LBE (lead–bismuth eutectic) primary coolant. LBE poses various challenges to bearing operation however. In addition to material attacks, it is a poor lubricant. The effects on the bearing are examined with extensive screening tests in LBE. The most widely implemented bearing monitoring sensor, the accelerometer, is not sufficiently reliable in this hostile environment. This paper outlines a torque-based method for remote monitoring radially-loaded deep-groove ball bearings in LBE. Challenges to existing torque models posed by inadequate lubrication are discussed. The parameters of the bearing torque most representative of the bearing condition are identified in both the time and frequency domains. These are correlated with the micro-analyses of selected test cases towards the validation of a diagnosis method for bearing degradation in LBE.

1. Introduction

The MYRRHA research reactor is being developed in Belgium for fast-spectrum material research, accelerator-coupled reactor studies, and transmutation of long-lived actinides. It will also serve as a demonstrator of the GEN-IV LFR (lead-cooled fast reactor concept) and all components will be submerged in a pool of liquid LBE (Sarotto et al., 2013; Abderrahim et al., 2012). The bearing is an essential component of the IVFM (in-vessel fuel manipulator) and is subject to extensive screening tests in the LBE environment. The functionality of DGBBs (deep-groove ball-bearings) in LBE at 200 °C is investigated for a range of bearing materials. The bearing has the principal functions to maintain position of rotating shafts relative to the housing, to reduce the rotational friction and to transmit loads. Failure to meet these functions for at least the period in between reactor maintenances would result in unscheduled reactor downtimes and important economic consequences. The core is being designed so that the bearing, a complex mechanical component not designed for the LBE conditions, is not a safety-critical component (Jezic von Gesseneck et al., 2012).

The current testing phase is scanning a wide array of DGBBs types. It is therefore interesting to reach some qualification of each candidate as quickly as possible. This can be achieved by connecting the live test information more closely to bearing (eg. material) properties, and earlier identification of the failure mechanisms. Such a method can also eventually be implemented in the reactor environment. Detecting faults at incipient or early stages would reduce the risks of bearing failure in between maintenances. The need to develop consistent bearing condition indicators is thus sourced in two motivations: firstly, to develop an understanding of the bearing failure mechanisms in LBE and secondly, to introduce a reliable bearing live monitoring tool.

Bearing fault detection and condition monitoring has been built on vibrations analysis over several decades. Tandon and

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Choudhury (1999) have made a comprehensive review of time-, frequency-, and combined-domain techniques. It covers improvements in noise-reduction, methods to extract defect frequencies from enveloped band-pass filtered peaks in higher resonance frequencies as well as the combined time-frequency-domain wavelet transform method proposed originally by Mori et al. (1996). More recent methods use statistical methods with the support-vector machine or neural networks and machine learning to detect abnormalities in vibrations patterns at different frequencies (Jardine et al., 2006). Numerous models have been developed for the prediction of vibration transmissions of bearings, from translation-constrained rigid-body, to six-degree-of-freedom (DOF) flexible systems (Rajab, 1982; Gupta, 1984; Lim and Singh, 1990).

Operation safety limits impose very low rotating speeds for the manipulator. Therefore the accelerometer or acoustic sensor for bearing monitoring must be sensitive at frequencies even below 1Hz. No such sensor which would function with sufficient reliability in LBE has been found. Therefore, information about the bearing condition must be obtained from a signal other than the vibrations. The rolling bearing is also commonly known as an anti-friction bearing thanks to the significant reduction of the friction moment in the axis of rotation by the rolling contacts. However, under Hertzian stresses and elliptical contact, rolling occurs only along two lines while the rest of the contact surfaces experience a relative micro-sliding. It is on this basis that Harris (Harris and Michael, 2006a,b) pioneered the first bearing friction moment models. Following the bearing friction instead of the vibrations allows the sensor to be transposed outside the hostile LBE environment. There are already sufficient studies to support this approach. A more detailed friction model for bearings has recently been developed by Houpert, 2002 taking into consideration numerous lubricant parameters. Greenwood and Williamson proposed one of the first microcontact models, studying effects of contact surface topographies (Greenwood and Williamson, 1966). Relevant practical studies include electric signal analysis of the stator current of one phase of a motor (Casada and Bunch, 1996), using the motor current as a sensor for its load (Riley et al., 1997), improving the defect feedback using the motor's airgap torque rather than the current (Hsu, 1995; Kliman et al., 1997). Bearing signature analysis methods from classical vibrations analysis have also been implemented on the torque signal (Smith et al., 2007).

Lubrication is an important factor in the bearing friction torque (see Appendix A). LBE interaction with stainless steels is subject to extensive research covering mechanisms including liquid-metal corrosion, oxidation, liquid-metal embrittlement, and environmentally-assisted cracking (Fazio, 2007). Lubrication remains one of the principal concerns for the bearing running condition in LBE however (Beznosov et al., 2013). Both roller bearing design and torque models are based on the principle of a sufficient lubricant film separating the rolling elements from the raceways. Stribeck determined that an elastohydrodynamic lubrication regime is ideal for the longevity of the bearing (Stribeck and Schröter, 1903; Halme and Andersson, 2010). The lubricant must be sufficiently thick to separate the rolling contact asperities, so as to avoid contact shocks and adhesive wear, but not so thick as to incur hydrodynamic damping effects. Dowson et al., 1977 and Hamrock, 1984 developed models for the minimum lubrication thickness in the roller bearings by considering the elastic deformation of the bearing contact surfaces (ie. roller-raceway) and the increase in the lubricant viscosity under high pressure in between the contact surfaces. LBE has a very low viscosity and is a poor lubricant under the near-static, high-load bearing test conditions (Fazio, 2007). The reactor contamination restrictions preclude the use of any additional bearing greases, oils or solid lubricants. An insufficient lubrication thickness may affect not only the degradation path of the bearing but also how this is reflected in the torque friction.

Despite the deviations from the lubrication basis of the torque models, the experiments in LBE evidence correlations between the torque signal and bearing defects. This paper presents an original investigation of torque-based diagnostics of different DGBB types in operation in the LBE environment. It is particularly interesting for the reader following the fourth-generation lead-cooled reactor concept, novel bearing environments with poor lubrication, or any bearing monitoring applications where accelerometers and acoustic sensors cannot be implemented. Further research and experience with torque-based defect monitoring in LBE will improve our understanding of the failure mechanisms and how they are reflected in the torque signal. With sufficient confidence in the correspondence, a reliable torque-based bearing condition monitoring system can eventually be implemented.

The paper is structured as follows: Section 2 reviews the approach implemented based on classical vibrations analysis and the challenges to bearing fault diagnosis in LBE, Section 3 describes the experiments, Section 4 lays out the results of the experiments and analyses. Section 5 concludes with the highlights and recommendations for further studies and applications.

2. The basis for a torque-based bearing study in LBE

The bearing lubrication thickness is a prime factor in the bearing running friction and hence any torque-based bearing analysis. The points in the bearing where the lubrication is at a minimum must be given particular consideration. These are in between the rolling elements and raceways. The pressure in the Hertzian contacts can reach the order of 10^9 Pa under within-specification external loads. Therefore sufficient lubrication must separate the asperities to prevent raceway degradation. Models allow the estimation of the lubrication regime based on the bearing and lubricant properties and the running conditions. Concretely, the λ parameter indicates the ratio of the lubrication thickness to the rms of the asperity peaks of the surfaces separated by the film. In order to have an elasto-hydrodynamic regime, λ in roller bearings should be at least 1 (IHS ESDU, 2010). The dimensionless models capture effectively how the minimum lubrication thickness in this regime is primarily dependent on the bearing materials, lubricant properties and the entrainment speed. The load has much less of an impact. Due to its opacity, and the specificity of rheological measurements, there is no data yet for the λ parameter for LBE. However, LBE has a kinematic viscosity of only 0.216 mm^2/s at 200°C (Fazio, 2007) (about five times less than that of water at 20°C). At very low rotating speeds of 10–50 rpm, λ is according to two models an order of magnitude below the minimum requirements for elasto-hydrodynamic lubrication. The bearings rolling contact asperities are consequently subject to plastic shear stresses and severe wear from the onset of testing (see Appendix B).

The basic rating life, L_{10}, is an estimate of the number of cycles to failure (in millions) of 10% of bearings from fatigue, ie. under adequate lubrication conditions:

$$L_{10} = \left(\frac{C}{P}\right)^3 \tag{1}$$

where P is the bearing load and C the dynamic load rating. While not applicable to bearings in LBE, it offers an appreciation of the drastic reduction from manufacturer's ratings of the bearing life in the tests due to the departure from bearing design operating conditions. This is based on the condition that the bearing degradation be principally from asperity contacts and wear rather than other LBE-related phenomena. This condition is supported by the micro-analyses. Radial loads were applied between 25% and 70% of the bearing static load rating, C_0. Out of 18 bearing runs in the screening tests, 8 did not reach 1/30 the basic rating life of the baseline