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Detection of sub-surface damage in wind turbine bearings using acoustic emissions and probabilistic modelling

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A B S T R A C T

Bearings are the culprit of a large quantity of Wind Turbine (WT) gearbox failures and account for a high percentage of the total of global WT downtime. Damage within rolling element bearings have been shown to initiate beneath the surface which defies detection by conventional vibration monitoring as the geometry of the rolling surface is unaltered. However, once bearing damage reaches the surface, it generates spalling and quickly drives the deterioration of the entire gearbox through the introduction of debris into the oil system. There is a pressing need for performing damage detection before damage reaches the bearing surface. This paper presents a methodology for detecting *sub-surface* damage using Acoustic Emission (AE) measurements. AE measurements are well known for their sensitivity to incipient damage. However, the background noise and operational variations within a bearing necessitate the use of a principled statistical procedure for damage detection. This is addressed here through the use of probabilistic modelling, more specifically Gaussian mixture models. The methodology is validated using a full-scale rig of a WT bearing. The bearings are seeded with sub-surface and early-stage surface defects in order to provide a comparison of the detectability at each level of a fault progression.

1. Introduction

Bearing failures are the leading source of downtime in Wind Turbine (WT) gearboxes and the root cause for this is attributed to Rolling Contact Fatigue (RCF) [1–3]. In the majority of loading conditions, fatigue damage begins its life at the *surface* of materials, where high stresses and imperfections due to manufacturing and surface wear coalesce and lead to crack initiation. The case in bearings is unlike typical fatigue damage. Hertzian contact mechanics dictates that, under the compressive load at the contact between a rolling element and a bearing, the location of maximum stress will lie a small distance under the surface at the point of contact between a roller and the bearing surface. This has some important consequences regarding the damage progression of a bearing. A growing crack will spend most of its time under the surface, where it has minimal impact on the operation of the rest of the system. However, once a crack emerges on the surface, the progression of failure is accelerated through contact with the rolling elements and this will generate spalling. At the point of initiation of spalling, the progression of damage is quick as debris is introduced into the rest of the mechanical system, thus accelerating the overall failure of the gearbox.

Currently, WTs are designed with an overall target lifetime of 20 years [4], a design requirement which extends to all of their subsystems. However, the average service life of wind turbine gearboxes often falls much below the 20 year target [5]. This is a problem; even though gearboxes are not the most unreliable subsystem, they do cause the most downtime [5]. Minimising gearbox failures is thus a key element in increasing overall wind turbine productivity [2]. Because bearing surface damage releases debris into closed-loop oil systems, sampling the oil quality and checking for debris within the oil system is, to date, still used as a reliable technique for diagnosing the overall condition of WT gearboxes [6,7]. It is also at this point that vibration-based monitoring systems are able to detect the presence of defects. The fact that bearing damage has reached the surface and introduced debris into the oil system motivates the need for detecting fatigue cracks in bearings before they reach this stage, so that preventive maintenance can be carried out and impact to the rest of the gearbox can be minimised.

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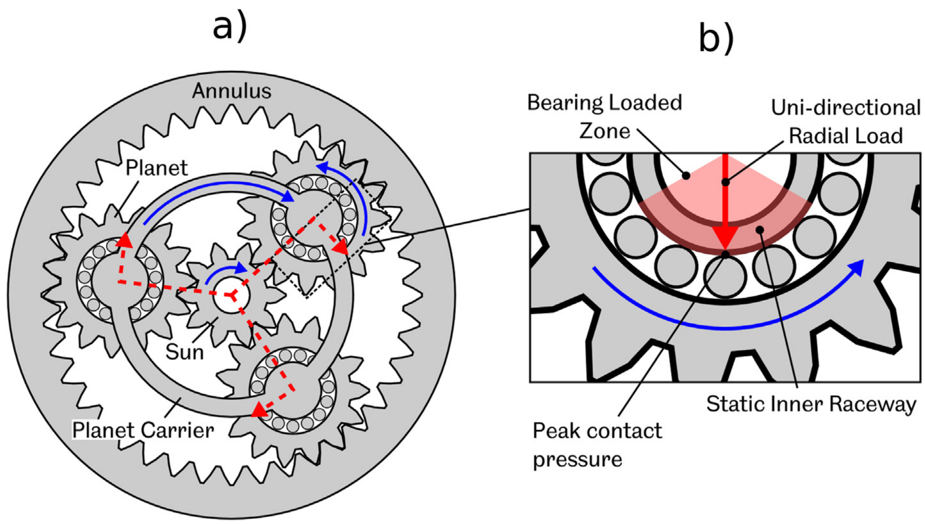

Fig. 1. a) Diagram showing gearing setup for a planetary gearbox. Note the planet bearings are constantly loaded in the torque direction, indicated by the red arrows. b) zoom-in to one of the planet bearings, highlighting the loaded zone [9]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Detecting *subsurface* damage at the incipient stage has been identified as a critical aspect of wind turbine condition monitoring [3]. Rolling contact fatigue is exacerbated in planetary gearboxes, where the bearing raceway is loaded exclusively in the torque direction. This exerts a compressive load on the same point along the circumference of the raceway, as illustrated in Fig. 1. In order to avoid the problems associated with the introduction of debris and accelerated failure, it is highly desirable to be able to detect the *incipient* failure of the bearing, at the point where a fatigue crack has just initiated. There are three critical aspects that will determine the outcome of a damage detection system [8]: 1) the physical sensing system, 2) the damage-sensitive features extracted from the data and 3) the damage identification strategy applied to those features. This paper addresses these problems. As for the physical sensing system, Acoustic Emissions (AE) are proposed as a measurement strategy. The damage-sensitive features extracted from AE data play a fundamental role in the ability to identify damage. In this paper, the state of the art of AE features are reviewed and compared and new features are proposed using advanced signal processing tools. Lastly, a rigorous damage identification strategy is proposed that addresses the key challenge of discerning operational and environmental effects from the damage-sensitive features. This is carried from a probabilistic modelling point of view, using Gaussian mixture models in combination with dimensionality reduction tools.

1.1. Subsurface cracks

The interest in subsurface cracks has grown since the realisation that fatigue cracks in gearbox bearings tend to start around non-metallic inclusions [10], introduced during the manufacturing process. The presence of these inclusions, coupled with high stress concentrations under the surface, leads to the development of fatigue cracks, often referred to as White Etching Cracks (WEC), White Structure Flaking (WSF) [11,12], or simply “butterfly” cracks due to their butterfly shape (with the “wings” following a path from the inclusion, out towards the surface). These cracks tend to grow in the region around 1 mm under the contact surface of typical WT bearings [13] and it has been proposed that their formation is driven both by chemical and mechanical processes. Chemically, it is the diffusion and release of hydrogen into bearing steel [14], through lubrication and water ingress that drives the formation of WECs. Mechanically, overload events arising from wind gusts, breaking and torque reversals drive stress concentrations around non-metallic inclusions to yield point and lead to the formation and growth of WECs. Since the realisation that inclusions in bearing steel directly lead to subsurface cracks, the quality control of the manufacturing processes has dramatically improved. However, inclusions will always be present even in today's high standard of steels. In fact, it has been shown that it is typically the smallest inclusions that lead to the greatest stress concentrations and therefore the development of WECs [12]. An example of a WEC at the initial stage of propagation is shown in Fig. 2, observed on a WT bearing section [12].

1.2. Damage detection with Acoustic Emissions

When considering the dynamic response of a system, it is a generally well-accepted principle that the physical size of damage is inversely proportional to the frequency at which its effects will be manifested in its dynamic response [15–17]. Furthermore, there is a well established relationship between the AE response of a metal and fatigue crack growth [18]. With this in mind, subsurface damage on bearings represents the smaller end of the scale, requiring relatively high frequency measurements, when

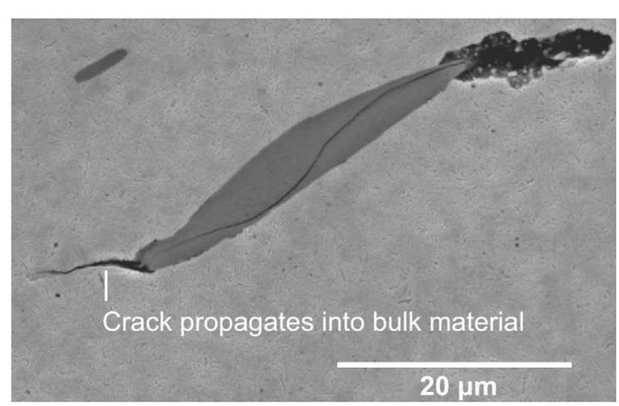

Fig. 2. Example of a WEC propagating around a non-metallic inclusion [12].