Reliability Engineering and System Safety 111 (2013) 45–57

Contents lists available at SciVerse ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Quantifying the added value of an imperfectly performing condition monitoring system—Application to a wind turbine gearbox

Adriaan Van Horenbeek*, Joris Van Ostaeyen, Joost R. Duflou, Liliane Pintelon

Centre for Industrial Management, KU Leuven, Celestijnenlaan 300A, BE-3001 Heverlee, Belgium

ARTICLE INFO

Article history:
Received 11 October 2011
Received in revised form
26 September 2012
Accepted 26 October 2012
Available online 5 November 2012

Keywords:
Condition-based maintenance
Condition monitoring systems (CMS)
Consequential or secondary damage
Life cycle cost (LCC)
Wind power

ABSTRACT

Implementation of a condition monitoring system is a difficult decision due to many uncertain parameters. This is certainly the case for the wind turbine industry where factors like long logistical times and weather conditions have a major influence on the economic benefit. One of the parameters that is neglected in most of the available literature is the performance of the condition monitoring system itself. In this paper a new concept for modeling this performance based on the *P–F* curve of different failure modes is presented. The concept is illustrated on an extensive case study for a gearbox of a wind turbine. A stochastic simulation model is constructed in order to quantify the economic added value of implementing an imperfectly performing condition monitoring system into a gearbox. This case study proves that a condition monitoring system generates an economic benefit compared to the currently applied maintenance strategy. However, the magnitude of this benefit depends strongly on the performance of the condition monitoring system.

1. Introduction

The importance of condition monitoring in maintenance is ever increasing in industry. Condition Monitoring Systems (CMS) can help to overcome unexpected downtime and reduce costs. This certainly applies for the wind energy sector, which is characterized by strong growth, where difficult accessibility of the turbine, high spare part costs and dependence on weather conditions forces wind turbine component manufacturers and operators to turn to condition monitoring systems. There exist several studies on how to quantify the added value of implementing a CMS in wind turbines in literature [1–4]. Most of these models assume that the state of a component can be perfectly monitored by the CMS. When looking at maintenance from a system rather than a component perspective, this is not always the case. A CMS is capable of predicting certain failure modes of different components in a system; however the CMS cannot predict every potential failure mode and costly false alarms are possible. It is thus important to take into account the effectiveness or performance of a CMS when quantifying the added value and defining the maintenance policy. The objective of this paper is to present a quantitative approach to determine the added value of CMS based on a static, stochastic model with Monte Carlo simulations, taking into account the performance of the CMS and the potential development of secondary damage. In this paper the *P–F* curve [5], where the point in time where an indication of deterioration of the component can be detected is referred to as a potential failure '*P*' and the point in time where the component suffers critical failure is referred to as functional failure '*F*', is used to model the performance of a CMS on different failure modes. Consequently a system level perspective is taken. The theoretical approach is illustrated by a case study of a gearbox in an onshore wind turbine. The economic benefit of implementing a CMS in an onshore wind turbine gearbox, from the point of view of the gearbox manufacturer, is determined. This case study illustrates the importance of incorporating the performance of the CMS into the calculation of the added value of a CMS, which is the major contribution of this paper.

1.1. Condition monitoring system performance

Many optimization models for condition-based maintenance are described in literature illustrating the economic benefit of implementing condition monitoring [6–12]. These assume that the degradation process of each considered component can be determined by different monitoring techniques (e.g. vibration monitoring, oil analysis). Based on this degradation process, decisions (e.g. time of inspection, time of maintenance) to achieve optimal maintenance are made. However, when realistically modeling such facilities a system perspective should be taken. It is not cost effective to accommodate every component in a production machine with its specific monitoring system. Therefore, condition monitoring systems

* Corresponding author. Tel.: +32 16 32 24 97; fax: +32 16 32 29 86.
E-mail address: Adriaan.vanhorenbeek@cib.kuleuven.be (A. Van Horenbeek).

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http://dx.doi.org/10.1016/j.ress.2012.10.010

(CMS) exist which are capable of monitoring different components and failure modes simultaneously. It is important to take into account the performance of the CMS, the ability to detect a failure mode and at what stage of deterioration it can be detected, when determining the added value of condition monitoring because the performance on each failure mode is not perfect. This determines the time to react to the potential failure of a component, which determines the ability to avoid long downtimes of the equipment by the possibility of planning maintenance actions in advance and preventing corrective maintenance actions. Preventing secondary damage on other components by detecting an incipient failure is another advantage of implementing a CMS. Also this benefit is dependent on the time when the CMS is capable of detecting a potential failure. The earlier the CMS detects the deterioration propagation, the less secondary damage will occur. A concept that is often used to describe the deterioration process of a component and the performance of on-condition maintenance tasks is the *P–F* curve and *P–F* interval [5]. Directly related to this concept is the proposed delay time model of Christer and Waller [13].

A balance between the performance and cost of the CMS should be found. This is certainly the case for critical machinery with a short *P–F* interval or long logistical waiting time (e.g. for spare parts). When the CMS only detects the failure in a late stage of the deterioration process, no time is left to react to the failure propagation and this results in costly corrective maintenance with potential secondary effects on other components. For this reason, the performance of a CMS and potential secondary damage propagation should be taken into account to really determine the added value of implementing condition-based maintenance. In this paper this will be addressed by using the well known *P–F* curve.

1.2. Condition monitoring systems for wind turbines

In the wind turbine industry the implementation of condition-based maintenance is intensively debated today. The time of performing a maintenance action on a wind turbine is dependent on several uncertain factors (e.g. weather conditions, availability of lifting equipment), which causes long logistical waiting times and possible consequential damage. This is certainly the case for offshore wind turbines, which makes condition monitoring tools and maintenance scheduling especially important for offshore applications. Together with the performance of the CMS, these factors play a crucial role in determining the added value. In reference [14] the importance of CMS performance and prevention of secondary damage is mentioned, but no methodology to model those is proposed. Wiggelinkhuizen and Verbruggen derive three major requirements of a CMS; detection of failure mechanism, detection on time and measurable health criteria [15]. Based on these requirements the performance of different condition monitoring systems is given. The performance is the potential of the CMS to move failure modes to lower failure repair classes which reduces the effect of failure. The impact of the effectiveness of a CMS on the economic benefit is also evaluated by McMillan and Ault [16]. A CMS effectiveness probability is introduced, which is a measure of how likely the CMS is to detect and diagnose a developing failure successfully. Nielsen and Sørensen [4] introduce a probability of detection, which models the reliability of an inspection on the wind turbine component. The probability of detection is directly linked to the damage level of the component. Although the importance of CMS effectiveness or performance is stated in these references, the CMS performance is never linked to the real deterioration process of a component, or is limited to a single component. In this paper these shortcomings are remediated by linking the CMS performance to the *P–F* curve of several components, which approximates the deterioration process of a component or system. Based on a life cycle cost (LCC) approach the added value of a CMS is determined for a case study on a wind turbine gearbox.

1.3. Contributions to state-of-the-art

The major contributions of this paper can be summarized as follows:

- A methodology, based on the well known *P–F* curve, is presented to model imperfect performance of a CMS and potential secondary damage. The performance of the CMS and secondary damage propagation are directly linked to the degradation and the corresponding *P–F* curve of the component.
- A methodology to quantify the added value of an imperfectly performing CMS is described. Moreover, the model is applicable to both cases where condition monitoring information is available and where it is not. The model is able to determine the minimal performance of a CMS necessary to generate economic value.
- The methodology is applied to an extensive case study of a wind turbine gearbox. In this way a complex multi-component system is considered.
- The results show the importance of the inclusion of imperfect performance and secondary damage in order to correctly evaluate the added value of CMS implementation.

In Section 2 the theoretical model on how the performance of the CMS and consequential damage propagation is modeled, based on the *P–F* curve, is presented. In Section 3 the theoretical approach is fitted to a real-life case study of an onshore wind turbine gearbox in order to illustrate the developed model. The results of this case study are given in Section 4 and finally future work and conclusions are stated in Section 5.

2. Theoretical model

In Sections 2.1 to 2.3 the developed theoretical model representing the performance of a CMS and the deterioration process of components, based on the *P–F* curve, is presented. Consequently the utilized approach to model the effect of secondary or consequential damage is discussed in Section 2.4.

2.1. The P–F curve

Moubray [5] examined failure patterns that can be detected by condition monitoring and highlights the importance of the *P–F* curve and *P–F* interval (Fig. 1). This curve visualizes the deterioration in time of a particular component. When a component is operated, it will start to deteriorate until it completely loses its capability to carry out its function. The point in time where the component suffers critical failure is referred to as functional failure ‘*F*’. A component can perform its regular task just up to this point. The point in time where an indication of deterioration

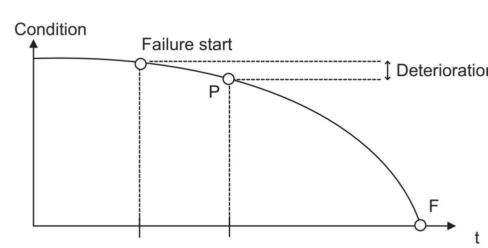

Fig. 1. *P–F* curve.