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Remaining useful life prediction of degrading systems subjected to imperfect maintenance: Application to draught fans

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ABSTRACT

Current degradation modeling and remaining useful life prediction studies share a common assumption that the degrading systems are not maintained or maintained perfectly (i.e., to an as-good-as new state). This paper concerns the issues of how to model the degradation process and predict the remaining useful life of degrading systems subjected to imperfect maintenance activities, which can restore the health condition of a degrading system to any degradation level between as-good-as new and as-bad-as old. Toward this end, a nonlinear model driven by Wiener process is first proposed to characterize the degradation trajectory of the degrading system subjected to imperfect maintenance, where negative jumps are incorporated to quantify the influence of imperfect maintenance activities on the system's degradation. Then, the probability density function of the remaining useful life is derived analytically by a space-scale transformation, i.e., transforming the constructed degradation model with negative jumps crossing a constant threshold level to a Wiener process model crossing a random threshold level. To implement the proposed method, unknown parameters in the degradation model are estimated by the maximum likelihood estimation method. Finally, the proposed degradation modeling and remaining useful life prediction method are applied to a practical case of draught fans belonging to a kind of mechanical systems from steel mills. The results reveal that, for a degrading system subjected to imperfect maintenance, our proposed method can obtain more accurate remaining useful life predictions than those of the benchmark model in literature.

1. Introduction

The past decade has witnessed a growing interest in prognostics and health management (PHM) in both academic and industrial communities, such as electronics, energy industry, aeronautics and aerospace, manufacturing, automotive industry, nuclear plants, and fleet-industrial maintenance [1–7]. In general, PHM is an enabling discipline consisting of technologies and methods to assess the reliability of a product in its actual life cycle conditions to determine the advent of failure and mitigate system risk [8]. The key components of PHM include two aspects, i.e., prognostics and health management [1]. The former is usually dedicated to predicting the remaining useful life (RUL) of a system using the available health condition information, while the latter focuses on performing appropriate management activities (e.g., maintenance schedule and

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inventory control) to achieve the required safety and economic performance based on the obtained RUL predictions [9]. So far, RUL prediction has been well recognized as the key of PHM program due to its fundamental importance in PHM implementation [10–16].

In practice, the RUL of a system is defined as the length of time from the current time to the end of the useful life, and RUL prediction often refers to finding the mean estimate or the probability density function (PDF) of the RUL [15]. A large volume of studies have been dedicated to RUL prediction during these years; see [15] and [16] for comprehensive reviews. The RUL prediction methods have basically evolved upon two major paradigms: physics-based and data-driven. Due to the rapid development of sensor and condition monitoring (CM) techniques [17–20], the latter has received considerable attention in the literature [15]. For the importance of CM techniques, the readers are suggested to see [15–22]. Traditionally, the RUL of a system can be obtained on the basis of the time-to-failure data of a population of identical systems. However, it is usually costly or time-consuming, or even impossible to collect the time-to-failure data in reality [15]. As an alternative, the degradation-data-based methods have been extensively developed in the literature to infer the RUL of a degrading system [10,12,15,21]. Although the degradation-data-based RUL prediction methods have gained momentum over the last few years, it needs to be pointed out that almost all of the existing methods in the literature assume that the degrading systems are not maintained or are maintained perfectly (i.e., to an as-good-as new state) [15,16]. In such cases, the system's degradation is accumulated gradually during its usage, and the RUL can be derived accordingly [23]. However, in many realistic situations, the engineering systems may be maintained imperfectly (e.g., by adding lubrication, partial replacement, balance adjustment, etc.), periodically or aperiodically, over the lifecycle. Actually, imperfect maintenance can restore the degrading system to any health condition level between as-good-as-new (i.e., perfect maintenance) and as-bad-as-old (i.e., minimal maintenance) [24]. We note that maintenance activities can also accelerate the degradation of a system (named as worse maintenance in the literature) or even make the system fail or break down (named as worst maintenance in the literature), and also the health condition of a degrading system can be brought to a state better than the as-good-as new state because of technology improvement, but these situations do not belong to the imperfect maintenance activities defined in literature, and hence they are outside the scope of this paper. For a detailed classification and definition of the maintenance activities, please refer to [24–26], and the references therein.

Take the draught fan (belonging to a kind of mechanical systems) in the steel industry as an example; the draught fan plays a significant role in modern steel-making process due to its ability in dust elimination and gas recycling [27]. In practice, the vibration level of a draught fan is usually chosen as the CM data (i.e. degradation data) to characterize its health condition. To be specific, as the draught fan degrades, the vibration measurements increase gradually, mainly due to the mechanical wear of the rotor and the fouling on the impellers. As a result, once the measured vibration data reach the specified threshold level, the draught fan is announced to be failed, thereby being replaced by a new one. However, to improve the performance of the draught fan and prolong its useful life, balance adjustment techniques are performed aperiodically during its usage process. The basic principle of balance adjustment is to reduce the vibration level by cleaning the fouling on the impellers, lubricating the electromechanical components, etc. The balance adjustment process can bring the draught fan to a better health condition with a lower vibration level, but it cannot restore the performance of the draught fan to an as-good-as new state due to the existence of irreversible degradation mechanisms, e.g., the mechanical wear of the rotor. Thus, balance adjustment technique is just a kind of imperfect maintenance activities for draught fans. Predicting the RUL of draught fans operating like this, is an urgent reliability and safety demand of the steel-making process in steel industry.

For an engineering system subjected to imperfect maintenance, the system's failure progression process will be slowed down, and accordingly system life will be extended. Thus, a more generalized case in RUL prediction domain is to predict the RUL of degrading systems subjected to imperfect maintenance. Unfortunately, scarce literature can be found to address the degradation modeling and RUL prediction issue under such a scenario. The most relevant studies in literature took the influence of imperfect maintenance activities into account in scheduling condition-based maintenance strategies. Guo et al. [28] presented a maintenance optimization model for mission-oriented systems based on the Wiener process, where the system may experience imperfect maintenance activities. Le and Tan [29] developed an optimal inspection-maintenance policy for a multi-state system by taking imperfect maintenance and inspection into consideration. Do et al. [30] proposed a proactive condition-based maintenance strategy considering both perfect and imperfect maintenance activities, where the degradation trajectory between two successive maintenance activities were modeled by the gamma process, and the influence of the imperfect maintenance activity was described by a continuous random variable. Although the imperfect maintenance activity was involved in the aforementioned studies, they only focused on the maintenance schedule issue for degrading systems, and thus the influence of the imperfect maintenance activities was not considered in the RUL predictions. Based on the above survey, it is concluded that the problem considered in this paper has not been uniquely solved in literature. Thus, it can be of interest to develop a new model to predict the RUL of an engineering system subjected to imperfect maintenance. The challenges of predicting the RULs of the degrading systems subjected to imperfect maintenance activities may lie in the following two aspects: first, how to construct the degradation model of the degrading system subjected to imperfect maintenance activities, and second, how to derive the analytical PDF of the RUL when the influence of imperfect maintenance activities is considered.

In response to the above questions, we first model the degradation path by a nonlinear model driven by Wiener process with negative jumps, which are utilized to characterize the influence of the imperfect maintenance activities on the system's degradation. Specifically, 'negative' means that the influence of the imperfect maintenance is opposite to the degradation trend of the system, i.e., bringing the degrading system's health condition to a better state, and 'jump' means that imperfect