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Preventive replacement for systems with condition monitoring and additional manual inspections

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ABSTRACT

Condition monitoring (CM) and manual inspection are increasingly used in industry to identify a system's state so that necessary preventive maintenance (PM) decisions can be made. In this paper, we present a model that considers a single-unit system subject to both CM and additional manual inspections. There are two preset control limits: an inspection threshold and a preventive replacement (PR) threshold. When a CM measurement is equal to or greater than the inspection threshold but is less than the PR threshold, a manual inspection activity is initiated. When a CM measurement is greater than the PR threshold, a PR activity should be carried out. The system's degradation process evolves according to a two-stage failure process: the normal working stage, which is from new to the initial point that a defect occurs, with the CM measurement coming from a stochastic process; and the delay-time stage, which is from the initial point that a defect occurs until the point of failure, with the CM measurement coming from an increasing stochastic process. We assume that a manual inspection is perfect in that it can always identify which of these two stages the system is in. In our study, the decision variables are the CM interval and the inspection threshold, and we aim to minimize the expected cost per unit time. We provide a numerical example to demonstrate the applicability and solution procedure of the model.

1. Introduction

Condition monitoring (CM) and manual inspection are maintenance activities that are commonly observed in industry (Christer & Wang, 1995; Grall, Berenguer, & Dieulle, 2002; Jardine, Joseph, & Banjevic, 1999; Jiang, 2010; Luo, Osypiw, & Irle, 2000; Nakagawa, Mizutani, & Chen, 2010; Vlok, Coetzee, Banjevic, Jardine, & Makis, 2002; Wang, 2008a, 2008b, 2011a; Wiseman, 2001). Both activities assess the system state and seek to identify any problems within it. However, the methods they use to achieve this are different. In general, CM utilizes some monitoring devices, whereas inspections are usually manual checks. CM can be carried out while the system is still operating, whereas manual inspections often require that the system be shut down. CM generally monitors the plant system on a periodic basis and obtains a sample of its measurements from the sensors on the plant system. However, in most cases, CM measurements are imprecise and uncertain. Such randomness of measurements may be due to measurement errors or other uncontrollable factors (Wang, 2006). This is why, in addition to CM, manual inspections are sometimes required, i.e., to ensure a thorough assessment of the system's condition and to confirm whether – based on the recommendation of CM – there is a problem or not (Christer, Wang, & Sharp, 1997; Jiang, 2010). For example, in Christer et al. (1997), a furnace is monitored by the induction ratio, and once this ratio is higher than a predefined overhaul threshold, the furnace is shut down for an overhaul. In addition, there is another threshold – the warning threshold – and if the induction ratio is between this threshold and the overhaul threshold, then the furnace is checked during a production window and overhauled, if necessary. In a water pump study by Wang, Scarf, and Smith (2000), the feedback from the CM provider contained three recommendations: to keep an eye on the pump whose vibration is near to the lower threshold of vibration; to shut down the pump for a thorough manual check if it is above the lower threshold; and to repair/replace the pump immediately if the vibration signal is above an upper threshold.

It is generally assumed that a manual inspection costs more than the equivalent CM since a manual inspection results in certain downtime. CM can be carried out without any supplementary manual inspections, and many past researches have been devoted to this area of study (Han & Song, 2003; Jardine & Banjevic, 2005; Kim & Makis, 2013; Kim, Jiang, Makis, & Lee, 2011; Maillart, 2006; Wang, 2008a; Wiseman, 2001). CM can be imprecise and the noise is considered to

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form a control-limit-type maintenance policy (Kim & Makis, 2013). Manual inspections can be carried out without any CM, and this is also an extensively studied subject (Cui, Loh, & Xie, 2004; Cui, Xie, & Loh, 2004; Nakagawa et al., 2010; Taghipour, Banjevic, & Jardine, 2010; Vaurio, 1994). However, we found no paper that modeled a similar scenario to the one we propose here, i.e., one which takes CM into consideration when modeling manual inspections. The closest scenario is found in the paper by Jiang (2010) where he modeled a CM case with sequential inspections. However, the inspection defined in Jiang's paper is the action used to obtain the accurate CM measurement rather than the manual inspection defined in our paper. Moreover, Wang (2011b) and Wu and Wang (2011) used a similar idea to ours when modeling two types of errors in statistical quality control.

The delay-time concept has been studied extensively and has been applied to model inspection practice (Wang, 2008b, 2012). This concept considers the system failure process as having two stages: the normal working stage, which is from new to the initial point that a defect is identified at an inspection; and the delay-time stage, which is from the initial point of the identifiable defect to failure (if the defect is left unattended). If an inspection is carried out during the delay-time, the defect can be identified and removed immediately or subsequently, depending on the quality of the inspection and defect removal. A number of case studies have successfully applied delay-time modeling techniques to industrial plant systems. See Wang (2012) for a recent review of delay-time models and their applications.

The principal idea of this paper is motivated from industrial observations and the literature on condition-based maintenance and inspection modeling. In particular, we attempt to model a situation where both CM and manual inspections are in place to assess the state of the system and perform preventive replacement (PR) – if necessary – under the delay-time concept framework. This is one of the main contributions of the paper, since, to our knowledge, condition-based maintenance models used in conjunction with the delay-time modeling technique have not yet been reported (Wang, 2012).

Another contribution of this paper is that we also try to overcome an existing problem in CM-based degradation models whereby system failure is only defined as the time that the CM measurement first reaches a predefined failure threshold, such as the first hitting time concept (Si, Wang, Hu, Chen, & Zhou, 2013). We argue that the system can fail before the CM measurement reaches the threshold, and such a threshold is mainly for PM, as we have observed in industry (Wang, 2011b, Wang et al., 2000). Our first argument is correct because the CM measurement has a stochastic relationship with the system state. Our second argument has been supported by industry observations, where the threshold is used to define the time for some PM actions rather than for real system failure. For this purpose, we model two related processes: the delay-time concept of a two-stage failure process, and the degradation process (with the measured CM data correlated with the two-stage failure process).

The remaining parts of this paper are organized as follows: Section 2 presents the problem description; Section 3 provides the modeling assumptions and notations; Section 4 details the cost model; Section 5 presents two detailed models based on some typical degradation processes; Section 6 presents numerical examples; and Section 7 concludes the paper.

2. Problem description

We consider a single-unit system subject to a dominant failure mode. As shown in Fig. 1(a), the failure process of the system has two stages: from new to the initiation of a defect (the normal working stage); and from this point to failure, if left unattended (the delay-time stage). The failed state is always identifiable, but the other two stages are random in their durations and are not directly observable unless a manual inspection is carried out. This follows the standard definition used in delay-time-based inspection models (Wang, 2012). Additionally, a CM process sampled at discrete time points reveals the system condition. Here, we need to consider that two errors (based on the obtained CM measurement) could occur: the CM measurement could indicate that the system is in the normal working stage while it is actually in the delay-time stage, and vice versa. The measured CM variable is related to the underlying failure process. It follows a combined stochastic deterioration process of non-decreasing trends with noise during the whole life of the system. However, such a process is also divided into two stages, each with different trends. There are two thresholds. One is the PR threshold, and if the CM measurement is above this threshold then the system is preventively replaced. We call this preventive replacement PR_1. The other is the inspection threshold, and if the CM measurement is between this threshold and the PR threshold then an in-depth manual inspection is performed on the system. Such an inspection is assumed to be perfect in that it can always identify which stage the system is in. If the system is identified as being in the delay-time stage, it is preventively replaced. We call this preventive replacement PR_2. If the system is not identified as being in the delay-time stage here, then no action is taken. A situation could also occur where a system reaches the end of its life before any PR, in which case a failure replacement occurs. All replacements are considered equivalent to renewals but with different costs. The decision variables in this problem are the CM interval and the inspection threshold, while we assume that the PR threshold is fixed according to engineering experience. In theory, with increased computational effort, more than two thresholds can be utilized. However, in practice we have observed that there are mostly just one or two thresholds. A two-threshold policy defines a three-state process that was popularly accepted and used in CM practice and in most CM related literature (Christer & Wang 1995; Wu & Wang, 2011). This problem can be observed in reality, e.g., in induction furnaces, battery systems, motors, industrial pumps and bearings. See Fig. 1 for an illustration of the delay-time concept and the replacement scenarios of such systems.

3. Model assumptions and notations

3.1. Model assumptions

The modeling assumptions used in this paper are as follows:

1. The system is a single-unit system subject to a single failure mode.
2. CM is carried out at a constant interval of t, which is a decision variable.
3. The system failure process develops in two stages: a normal working stage and a delay-time stage with degradation developing.
4. The CM measurement thresholds have two control limits. First, regarding the PR threshold, once the CM measurement is above this threshold, the system is preventively replaced without further manual inspection. This threshold is set by industrial standards or engineering experience and should be strictly followed. Second, regarding the inspection threshold, if the CM measurement is between the inspection and PR thresholds, an in-depth manual inspection is carried out on the system. Such an inspection is perfect in that it can always identify which stage the system is in. Once the inspection reveals that the system is in the delay-time stage, the system is also preventively replaced. However, if the inspection reveals that the system is in the normal working stage then the system does not need any preventive action.
5. The system can reach the end of its life before any PR. A failure replacement then occurs.
6. All replacements are considered to be equivalent to renewals but with different costs. We assume the average cost of a failure renewal is higher than the average cost of a PR_1 or PR_2 renewal, which are both equal.

Assumption 1 is common in CM practice, since CM is usually sensor-based in order to monitor an important component system