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Prognostic control-enhanced maintenance optimization for multi-component systems

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ABSTRACT

In the last decades, the fast evolution of the industrial scenario has boosted the economic relevance of maintenance in all sectors of industry, and interests in maintenance can be expected to continue increasing in the next future. Maintenance has gained in importance as a support function for ensuring equipment availability, quality products, on-time deliveries, and plant safety. This paper presents a novel maintenance optimization strategy for multi-component systems that uses *local prognostic control* to improve health statue of operating systems at component-level and solves a *global optimal problem* to find proper maintenance interval at system-level, the combination of which can increase maintenance economy effectively. The proposed strategy can be demonstrated by a case study of braking system of rail vehicles. Compared with traditional dynamic maintenance methodologies, the results show that the maintenance cost can be reduced significantly when both health-oriented prognostic control and global optimization are utilized together.

1. Introduction

Modern vehicle systems have growing demands for improving safety and survivability when suffering unexpected faults or failures [1]. Thus, life cycle cost (LCC) has been becoming a focus of attention in design and operation. LCC works as a tool to determine the most cost-effective option among different competing alternatives to purchase, own, operate, maintain, etc. To achieve better LCC, program optimization is often desired. A good optimization strategy can be not only considered in stage of design and manufacturing, but also in stage of operation and maintenance.

To the perspective of *maintenance*, there are mainly two types of methodologies: Time-based maintenance (TBM) and condition-based maintenance (CBM). For TBM, preventive maintenance decision is based on system age and knowledge of statistical information on the system lifetime [2,3]. In contrast, CBM consists of advanced maintenance techniques, relying on the diagnostic/prognostic of the system condition over time [4–6]. In further, prognostics and health management (PHM) technology acquires big developments in recent decade. Various of PHM strategies [7–10] have been developed that pertain specifically to the phase of predicting future behavior, including remaining useful life (RUL), on the basis of current operating state and schedule of required maintenance actions to maintain system health [11]. Based on PHM technology, some embedded *control* strategies, such as automated contingency management (ACM), have been proposed and applied to vehicles such as aircraft [11–13], helicopters [14], ships [15], etc. These control strategies aim to optimize available components and control modes so that systems can continue to operate within an acceptable and stable regime [11].

Even though lots of maintenance strategies have been developed in the past decades, the effective ones for *multi-component systems*, such as complex vehicles, still are regarded as a big challenge, because those existing strategies cannot be adapted directly to multi-component systems [16], in which interdependencies may exist between components [17], and the deterioration process or failure of a component may affect the lifetime distribution of others.

Permanent magnet synchronous motors (PMSM)-driven rail vehicles [18] are such typical multi-component systems, which utilize permanent magnet to generate electromagnetic force for traction and brake. Accordingly, demagnetization is regarded as a serious fault of PMSMs, when which occurs, the wear of brake shoes will increase obviously due to the decreased electric brake force. The existing researches of multi-component systems usually resort to maintenance plan optimization to achieve the lowest maintenance cost [19–21]; however the nature of interaction in multi-component still can lead to severe safety accidents and failed maintenance.

To cope with these relevant challenges and achieve economic maintenance cost, this paper proposes a novel prognostic control-

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enhanced strategy for maintenance optimization. At first, nonparametric modeling technology is employed for *local* prognostic control to improve health statue of operating systems at component-level, then a *global* optimal problem is solved to find proper maintenance interval at system-level. This developed scheme combines advantages of components lifetime extension by optimal control and maintenance interval extension by maintenance plan optimization. Therefore higher safety and lower maintenance cost for complex multi-component systems can be achieved in contrast to traditional maintenance strategies.

The remaining parts of this paper are organized as follows. Section 2 introduces the basic methodologies applied in maintenance and control optimizations. The fault mechanism of Electro-Pneumatic Compound (EPC) braking systems of PMSM rail vehicles is described and in Section 3, the proposed framework of prognostic control-enhanced maintenance optimization is developed in detail. Section 4 describes an experiment to demonstrate the effects of the proposed scheme on the EPC braking system. Finally, conclusions are presented in Section 5.

2. Background knowledge

This section covers a brief introduction of the relevant knowledge used in the proposed strategy and experiment. The materials contain the development of maintenance strategies, health-oriented control thoughts and typical fault mechanism of EPC braking systems.

2.1. Maintenance strategies of industrial equipment

According to different maintenance approaches, two categories of maintenance are involved [22]: corrective maintenance and scheduled maintenance.

Corrective maintenance (CM) is the oldest approach to maintenance and is nowadays still adopted in some industries, especially for equipment which is not safety-critical and whose spare parts are easily available and not expensive. Under the CM strategy, the components are operated until failure; then, repair or renovation actions are performed.

Scheduled maintenance policies can be further divided into three groups: Preventive Maintenance (PM), condition-based maintenance (CBM) and predictive maintenance (PrM). Preventive maintenance (PM) encompasses all actions performed in an attempt to retain an item in specified conditions by providing systematic inspection, detection and prevention of incipient failures. A huge number of PM models and optimization methods have been introduced with the aim of reducing failures, for safety reasons, and unplanned down time, for economic reasons. For example, the so-called ‘age-replacement’ models (a very well-known class of PM models [23]) consider that a component is preventively maintained at some predetermined age or repaired at failure, whichever comes first.

In recent years, the relative affordability of on-line health monitoring technology has led to a growing interest in new maintenance paradigms such as the CBM and PrM. These are founded on the possibility of monitoring the system to obtain information on its conditions. On this basis, a decision is taken on the next maintenance action. This allows a dynamic approach to maintenance based on failure anticipation, aimed at optimizing the equipment lifetime usage.

2.2. Health-oriented control thoughts

As an important engineering approach for CBM and PrM, PHM can provide the essential technical supports. Furthermore, inspired by biological immune engineering, some researchers recently are increasing attentions on PHM applications into control strategies, such as automated contingency management (ACM) [12], engineering immune system (EIS) [24] and fault self-recovery (FSR) [25], etc. Principles and brief introductions of these methodology are listed in Table 1. Similar to maintenance optimization problems, these health-oriented control thoughts aim to achieve optimal performance in reliability, availability, maintainability and safety (RAMS) that also lead to improved LCC.

Fig. 1 shows a typical health-oriented control process in which PHM is embedded into a control level. At the higher echelons, mission re-planning and midlevel ‘intelligent’ controls are exercised to safeguard the operational integrity, whereas gain scheduling is practiced at the lowest level to ascertain systems stability. Different control strategies can be selected that depend on mission plan and capability assessment result from PHM. For healthy systems, *performance control* is the only attention that can be referred as common control strategy. When health of components/ subsystems degrades, the life extending control or fault tolerant control should be considered. The *life extending control* aims to extend remaining useful life of “problem” components by changing load profile or degrading operation performance, while the *fault tolerant control* devotes to preserve previous performance by isolating faulty units or triggering redundancy.

Key assumptions of health-oriented control strategies usually include [7]:

- The failures or system parameter changes are unanticipated.
- After the appearance of a failure, the system operates in an emergency mode with another criterion until the failure is recovered.
- Nonstandard techniques, effectors, and configurations may be required.
- The available reaction time is small.
- The handling qualities of the restructured/reconfigured system may be degraded.
- The failure, in general, may influence the system behavior and stability.

With the strategy of health-oriented optimal control is imported, the RAMS of systems will be improved so that maintenance interval can be extended dynamically.

2.3. Demagnetization fault mechanism of EPC braking system

For multi-component systems, such as PMSM-driven rail vehicles, fault or performance degradation of single component can propagate to interactive components even high-level systems. Therefore, it is imperative to know the propagation mechanisms of main faults.

EPC brake is one of the core systems in PMSM-driven rail vehicles, including electric brake and pneumatic brake. The electric brake is executed in prior by PMSM that works as a generator to provide braking torque. When the electric braking torque is insufficient, pneumatic brake that utilizes braking shoe to exhaust kinetic energy can compensate the braking torque. As two main components in EPC, PMSMs are much more likely to suffer injury demagnetization failure due to inner high temperature and vibration, while brake shoes usually face wear failure due to thickness degradation. What is more, demagnetization of PMSMs can accelerate wear of braking shoes. The interactive fault propagation mechanism can be described in Fig. 2. The dashed lines stand for the relationship of braking force F and axle velocity v in the demagnetization condition, while solid ones indicate their relationship in the healthy condition. The colored parts show the changes of braking energy from pneumatic braking to electric braking. When demagnetization occurs, a part of the braking energy, originally exhausted by electric braking, will be exhausted instead by pneumatic brake. According to the Archard wear theory [26], wear ratio will increase. Therefore, demagnetization will not only cause a fault to PMSMs, but also induce wear to brake shoes. It takes a typical multi-component maintenance problem.

The general first principle to simulate PMSM output property is the d-q equation model [27]. At braking stage, three phases of the motor are connected to braking resistors [18], as shown in Fig. 3: