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Prognosability study of ball screw degradation using systematic methodology

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As a critical mechanical component that converts rotary motion to linear motion with high precision, the ball screw has drawn a lot of attention in the field of Prognostics and Health Management (PHM). However, prognosis of the ball screw degradation has not been fully discussed yet in the current literature. This paper first justifies the prognosability of a ball screw via experimental studies, then proposes a systematic methodology for ball screw prognosis to implement the fault diagnosis, early diagnosis, health assessment and remaining useful life (RUL) prediction. Meanwhile, sensor-less and sensor-rich strategies are investigated and benchmarked in the experimental studies. The results demonstrate that the ball screw degradation behavior is available for prognosis and the proposed methodology can effectively help users to implement PHM analysis. Besides, the benchmark studies between sensor-less and sensor-rich strategies also achieve several practical conclusions that are valuable for real-world applications.

1. Introduction

The ball screw is an important mechanical device that is widely employed to convert rotary motion to linear motion with high precision. Application of ball screws can be found in many engineering systems which require very precise position control, such as the feed drive system for a machine tool and the high precision leveling system for aircrafts and missiles. In practice, it is found that the operation risks may increase significantly as the ball screw assembly degrades over time, since the ball screw degradation can have a huge impact on the control precision. For example, the preload loss will reduce the stiffness of the ball screw assembly and eventually such kind of degradation would lead to position accuracy loss. Therefore, prognosis of the ball screw holds great practical and academic value.

Prognosis of the ball screw is intrinsically challenging due to the complex motion trajectory of the rolling elements and the limited space for sensor installation. To monitor the preload loss, one simple way is to install a force sensor to measure the no-load torque of the ball nut. However, this method is rendered impractical due to the cost of the force sensors and the complication of sensor installation. As an alternative solution, Hilbert-Huang Transform (HHT) and Multiscale entropy (MSE) analysis are utilized to process vibration data for diagnosing the different ball screw preload levels [1]; vibration energy at a

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specific frequency range is also proposed to diagnose different preload loss levels [2]. Considering the vibration signal contamination from other components like bearings, which is not related to ball screw preload, Angular Velocity Vold-Kalman Filtering Order Tracking (AVVKF-OT) was proposed to isolate vibration signals merely from the ball screw nut and then ball pass frequency was used to detect the onset of preload loss [3]. To study the feature extraction strategy from vibration data, Jin et al. [4] proposes to apply a wide range of signal processing techniques to extract features from the time domain, frequency domain and time-frequency domain, then use Fisher Criterion to select the most effective features to diagnose different preload levels. Besides the vibration analysis, built-in signals from controller have been also explored. The Hilbert-Huang Transform (HHT) and Multiscale entropy (MSE) analysis have been employed to process the motor current signal for preload loss diagnosis [5].

Summarizing the related works in current literature, it is found that most of the previous works mainly focus on the diagnosis of ball screw failures and the exploration of the fault mechanism. However, prognosis of the ball screw degradation has not been fully discussed yet in the current literature. According to the '5C' framework for machine prognostics and health management (PHM) that is depicted in Ref. [6], machine prognosis should include fault diagnosis, early diagnosis, health assessment and remaining useful life (RUL) prediction. Before the PHM implementations, feasibility studies are needed to justify the prognosability of the system [7]. To study the ball screw degradation systematically, this research aims to address the following two engineering problems: (1) to justify the availability of ball screw for prognostic analysis; (2) to propose a systematic methodology for ball screw fault diagnosis, early diagnosis, health assessment and RUL prediction. Besides, this research also investigates the necessity of add-on accelerometers for PHM purpose.

To tackle these engineering problems, this research first designs new experiments to study the degradation behavior of a ball screw and then proposes a systematic methodology for ball screw prognosis. The contribution of this paper can be summarized from four aspects: (1) two different experimental studies are designed respectively to discuss the availability of prognostics and to validate the effectiveness of the proposed prognosis methodology. The prognosability of the ball screw system is justified by diagnosing the system degradation at different severity levels in Experiment 1 and the effectiveness of the proposed method is demonstrated by the accelerated life test (ALT) in Experiment 2; (2) a systematic methodology for the ball screw prognosis is proposed and validated. To make the proposed methodology more practical and robust, only the off-the-shelf machine learning algorithms are employed; (3) the sensor-less strategy (using built-in sensors only) and sensor-rich strategy (using extra accelerometers) for PHM analysis are benchmarked in all the case studies. (4) Conclusions made in this work hold great practical value, which clearly indicates the suitable signal sources for ball screw prognosis based on the proposed methodology.

The rest of this paper is organized as follows; The engineering problems to be addressed in this study are clearly stated in Section 2. Section 3 elaborates on the experimental studies as well as the proposed methodology. In Section 4, the analysis results are presented and discussed. The conclusion remarks are presented in Section 5.

2. Problem statement

The ball screw preload condition has major impacts on the system stiffness and will eventually affect the manufacturing precision as the mechanical parts wear out. In practice, preload loss is observed as one of the most common phenomena for ball screw degradation, and the preload condition of the ball nut and guideway will get worse over time. However, the monitoring of preload loss is still challenging since the motion of a ball screw in operation is non-stationary and dynamic. Vibration analysis has been explored in the recent literature to detect the preload loss. GH. Feng et al. [8] proposes a dynamic model of a ball screw preload adjustable feed drive system to build the relationship between preload variation and vibration signal spectrum during the operation. Tsai et al. proposes a ball pass frequency detection method using Angular Velocity Vold–Kalman Filtering Order Tracking (AVVKF-OT), by which the onset of ball screw preload loss is identified [3]. However, it is found that the vibration data from harsh manufacturing environments can be easily contaminated by the unwanted noise [8,9] and also it is challenging to directly sense the ball nut vibration due to the accessibility of the space [10]. To unveil these obscurities, this research compares both the sensor-rich and sensor-less strategies for ball screw PHM analysis. The sensor-less strategy only relies on the built-in speed and torque signal from controller, while the sensor-rich strategy considers data from both the controller and the add-on accelerometers. To make the PHM analysis for the ball screw assembly comprehensive, the preload conditions of both ball screw and guideway are investigated at three different levels – good preload condition, mildly degraded and fully degraded.

This research studies the ball screw PHM following the framework in Fig. 1 and primarily focuses on the early diagnosis, health assessment and RUL prediction of the ball screw assembly. Early diagnosis in this research includes accurate classification of different failure modes (primarily ball-nut preload loss and guideway preload loss) at different degradation levels. The early diagnosis study is introduced first since it builds the foundation for subsequent PHM analysis. As depicted in Fig. 1, the ability to classify the different degradation levels is a pre-requisite of the subsequent health assessment, which justifies the availability of prognosis for the ball screw assembly [11]. To study the early diagnosis of the system and justify the availability for subsequent prognosis tasks, a number of comparative test runs are designed in Experiment 1 which will be detailed in next section. The health assessment and RUL prediction aim to model the slow degradation of the ball-screw assembly using a univariate health series and then predict the RUL of the system based on the health series, as shown in