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An adaptive-order particle filter for remaining useful life prediction of aviation piston pumps

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Abstract An accurate estimation of the remaining useful life (RUL) not only contributes to an effective application of an aviation piston pump, but also meets the necessity of condition based maintenance (CBM). For the current RUL evaluation methods, a model-based method is inappropriate for the degradation process of an aviation piston pump due to difficulties of modeling, while a data-based method rarely presents high-accuracy prediction in a long period of time. In this work, an adaptive-order particle filter (AOPF) prognostic process is proposed aiming at improving long-term prediction accuracy of RUL by combining both kinds of methods. A dynamic model is initialized by a data-driven or empirical method. When a new observation comes, the prior state distribution is approximated by a current model. The order of the current model is updated adaptively by fusing the information of the observation. Monte Carlo simulation is employed for estimating the posterior probability density function of future states of the pump's degradation. With updating the order number adaptively, the method presents a higher precision in contrast with those of traditional methods. In a case study, the proposed AOPF method is adopted to forecast the degradation status of an aviation piston pump with experimental return oil flow data, and the analytical results show the effectiveness of the proposed AOPF method.

1. Introduction

An aircraft hydraulic power supply system provides high-pressure fluid for the actuation system, braking system, landing gear system, and other sub-function systems. As the power source of an aircraft hydraulic system, an aviation piston pump's performance influences flight safety directly. Therefore, an aircraft prognostics and health management (PHM) system appears to keep high reliability and long life of an aerial piston pump. In PHM technologies, an accurate estimation of the remaining useful life (RUL) is the most difficult issue because it is related to the failure physics and stress spectrum imposed on a hydraulic pump. Since the structure of an aviation piston pump is very complicated, its failure generation and development are comprehensively affected by inner frictional pairs with uncertain characteristics. Statistically, an

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aviation piston pump shows variant degradation paths under diversiform operating conditions, which unavoidably brings about a great deal of uncertainties and difficulties in the analytic solution of the RUL. Although the life of a certain type of aviation piston pump can be obtained through tens of thousands of hours of experiments under a fixed spectrum, it is difficult to give the exact RUL under an arbitrary condition. A prognostic estimation method of RUL is imminently needed, which will highly benefit the reduction of costs by providing the possibility to define predictive maintenance strategies and prolonging useful life.

Over past decades, a lot of research has been conducted in estimating the RUL of machinery. The methods can be generally divided into two categories[1]: data-driven methods and model-based methods. Typical data-driven methods based on machine learning are artificial neural networks (ANNs) and the hidden semi-Markov model (HSMM). Zangenehmadar and Moselhi[2] used an ANN to assess the RUL of pipelines successfully in which more than 80000 groups of data were used for training. Dong et al.[3–5] applied the HSMM function for machine health prognosis and verified the method by using data from a real hydraulic pump health monitoring application case study. In fact, the data used for training were far more than the sample size of a certain type of aviation piston pump. Several thousand of hours were taken to obtain only one set of lift-cycle data of an aviation piston pump.[6] He et al.[7] presented a health monitoring and prognostic method using the PSO-SVM to predict the RUL for an axial piston pump. The small sample problem is what makes an aviation piston pump distinguish from traditional machinery. Model-based methods like physics-of-failure (POF) and filter-based methods are also widely utilized for prediction of component life. Liu et al.[8] developed a failure physics model for the creep fatigue of a piston, and the degradation mechanism was analyzed for prognosis. Lamoureux et al.[9] defined a health indicator to describe the degradation of an aircraft engine fuel pumping unit by using a linear regression method. To build a model by POF, the mechanism needs to be known firstly. Thereby, this kind of method can hardly be used in a complicated system like an aviation piston pump whose failure mechanism is still under research. Filter-based functions take advantages in combining system models with experimental data. For linear systems with Gaussian noise, Kalman filter (KF) is a commonly used prognostic technique, and its effectiveness has been proven in many works.[10–13] Extended KF (EKF) and unscented KF (UKF) methods are modified KFs to cope with non-linear systems while limitation is shown in some systems with high nonlinearity.

According to the fact that the sample size of an aviation piston pump is very small, a data-driven method would not be a good choice for life prediction. Among model-based methods, particle filter (PF) has shown great advantages as an efficient prognostics tool in handling the uncertainty and noise affecting measurements.[14] A dual-particle-filter method was used to estimate the state of charge for power Li-ion batteries.[15] To address the particle impoverishment problem, a modified particle filter, named intelligent particle filter (IPF), was proposed by Yin and Zhu.[16] Miao et al.[17] introduced an improved PF algorithm – unscented particle filter (UPF) into battery RUL prediction, and the analytical results showed that UPF could predict the actual RUL with an error less than 5%. Zio et al.[18–21] improved the method a lot by applying PF functions in different degrading systems, and the framework to estimate the RUL of nonlinear components provides ideas for the prognosis of pump systems. However, to adopt the method, a degrading model should be built. Some parts of a piston pump has been modeled like a friction mechanism model of oil between the valve plate and the cylinder block in axial piston pumps[22] and a wear mechanism model of friction pairs[23] while a physical model that can be used for prediction has not been proposed.[24,25] For a system that is difficult to be modeled, an empirical model or a model built according to historical data is used to describe the degrading process. Fagogenis et al.[26] proposed an auto-regressive (AR) model with an RUSBoost classifier, and a CMAPSS dataset provided by the NASA AMES research center was used to verify the performance of computing the RUL of turbofan engines. A gray prognostic model based on the Markov process was used for a gas turbine compressor's state estimation.[27] These kinds of models compromise the merits of data-driven models and have less demand in data quantity.

To address the problem mentioned above, a novel particle-filter based prognostic method for an aviation piston pump's RUL prediction, named adaptive-order particle filter (AOPF), is proposed in this work. Though the wear mechanism of the pump is complex, the return oil flow has been proven to be a logical characteristic of the pump internal wear status.[23] The degradation of the pump is reflected by the increase of the flow while the flow shows a non-smooth characteristic that violent fluctuation occurs randomly. The main task is to handle the uncertainties which are classified in three categories.[28] The first one is the uncertainty of future degradation progress of an aviation piston pump which may be caused by unknown load spectrum and random environment factors and will result in different degrading paths, because of which model should be modified timely in order to maintain accuracy. Secondly, in modeling, an incomplete data set and some sufficient but not necessary assumptions and simplifications may prevent a prognostic model from precision. A model with biased parameters will influence the performance in prediction. Thirdly, data collected by sensors and acquisition systems are often accompanied by measurement noise.[29–31]

The rest of this paper is organized as follows: Section 2 describes the particle filtering framework for estimating the RUL; in Section 3, the proposed AOPF technique is described in detail; in Section 4, the application of the method is verified by an experimental test, and a comparison with traditional methods is discussed; in Section 5, some conclusions and remarks are drawn.

2. Adaptive-order particle filter based prognostics

2.1. Degrading characteristics of aviation piston pumps

There are four main friction pairs in a typical aviation piston pump: pair of the cylinder block and the valve plate, pair of the swash plate and the slipper, pair of the slipper and the piston, and pair of the piston and the cylinder block. Under normal circumstances, oil film exists between the friction pairs. It is shown that wear occurs and becomes serious with an increase of the serving time.[22] The wear process is accompanied by emerging abrasives. The accumulative amount of wear particles can indicate the degree of wear to