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Adaptive and robust prediction for the remaining useful life of electrolytic capacitors

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ABSTRACT

In integrated avionics systems, ensuring the high reliability and lengthening the life cycle of the avionics circuits become more and more important. This paper proposes an adaptive and robust prediction method to estimate the state of health and predict the remaining useful life (RUL) of electrolytic capacitors, which is one of the most significant components in avionics circuits. Based on an accelerated aging experiment performed by NASA, the degradation mechanism of electrolytic capacitors is analyzed. According to the capacitance loss data, a combination of the Verhulst model and the exponential model is adopted as the empirical model, and the unscented Kalman filter is applied to generate the proposal distribution of the particle filter to track the degradation path. Regarding the particle impoverishment, a particle swarm optimization algorithm is adopted to optimize the residual resampling step to improve the prediction accuracy. Also, adaptively adjusting the number of particles is introduced to make the algorithm more computationally efficient. Compared with the conventional particle filter algorithms, the experiment on the electrolytic capacitors degradation data indicates that the proposed novel method is able to provide a higher accuracy for the remaining useful life evaluation.

1. Introduction

To ensure the high efficiency of systems and avoid the potential considerable economic loss, research concerning the remaining useful life (RUL) prediction for safety-critical systems, is evolved as one of the most prominent areas in Prognostics and Health Management (PHM). Generally, RUL prediction can be implemented using data-driven approaches, model-based approaches [1,2]. The data-driven prediction methods not only contain intelligent methods [3-6], such as the relevance vector machine, but also include the methods based on the mathematical statistics. Model-based methods involve explicit mathematical functions to describe the physics and failure modes of systems. In [7], David et al. applied a method using the particle filter (PF), the extended Kalman filter (EKF) and unscented Kalman filter (UKF) to resolve the estimation and RUL prediction of electronic components or mechanical components. Degradation models in the model-based methods are always established with empirical models and analytical models. However, for complex systems, it is difficult to develop accurate analytical models especially when the systems are operated in noisy or uncertain environments [8]. Therefore, the degradation models in the model-based methods are usually built with empirical models.

Due to the fact that the electronic components [9,10] are widely applied in practical applications, research about their remaining useful life evaluation, including the battery [11-13], MOSFETs [14,15], capacitors [16-20] has been a growing focus in literature. In these critical electronic components, capacitors are usually used as filtering elements in power source unit, which is a very important subsystem for modern avionic systems. An electrolytic capacitor consists of a cathode made of aluminum foil, a separator paper, an anode mainly made of electrolyte and an aluminum oxide layer which is the dielectric on the anode foil surface [21]. The widely used electrolytic capacitor in the avionics circuits makes it play a very important role. Thus, there is a pressing need to develop a method facilitating its remaining useful life evaluation. For the degradation mechanisms, there are three main factors, i.e., the electrolyte evaporation, the leakage current, and the increase of the internal pressure. However, literature review indicates that there existed very few papers studied the RUL prediction method for the electrolytic capacitors which are quite critical to various electrical systems. For example, Biswas et al. [17] developed a method to predict the RUL of the electrolytic capacitors using Kalman filter (KF). A nonlinear least-squares regression algorithm was applied to estimate the parameters of the empirical degradation model which was established with the

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exponential model in [18]. Existing works relating to PHM of the electrolytic capacitors were mostly focusing on the design of the accelerated aging experiments and the corresponding experimental setup which aims to obtain the degradation datasets to support the estimation of RUL of the electrolytic capacitors, such as [18-20]. Thus, to fill this gap, this paper emphasizes the prediction algorithm and proposes a new prediction method to estimate the state of health (SOH) and predict the RUL of the non-solid electrolytic capacitors.

The research regarding the RUL prediction of the electrolytic capacitors includes two critical aspects. The first is the empirical model applied in the prediction method. In general, most of the works used the exponential model as the degradation model due to its mathematical simplicity. For example, Biswas et al. [17], Xing et al. [22], and Miao et al. [23] all adopted the exponential model as the empirical model to model the degradation path. Though the exponential model is one of the most common candidates for the empirical model, there exists a disadvantage of being excessively simple and such inflexible model cannot track the real degradation efficiently and accurately. The second is the following prediction algorithm. Most of the concerned papers adopted the methods such as conventional PF and KF to avoid the limitation of the data-based method. For example, Biswas et al. [17] presented a KF in conjunction with an exponential degradation model for the RUL prediction of the electrolytic capacitors. Besides, Liu et al. [24] implemented the precise estimation of the component RUL with a PF-based prediction framework as well. Therefore, the conventional PF is an effective tool to predict the RUL of the electrolytic capacitors.

However, there are some weaknesses existing in the conventional PF which can seriously reduce its performance [20,25]. The first one is the particle degeneracy, and it occurs after several times of the particles iterations when the particle weights are concentrated on few particles, which makes the particles set unable to represent the true posterior probability distribution. The solutions for such defects are mainly in two aspects, i.e., choosing a good importance density function and the implementation of particles resampling. Generally, conventional PF always adopts the transfer prior distribution as the proposal distribution due to the mathematical convenience. However, this choice has a serious problem that it almost ignores the corrective impacts from the latest measurements towards the importance weights. In order to select a suitable proposal distribution, Miao et al. [23] proposed an improved PF by adopting UKF to generate the proposal distribution with a small variance in conventional PF to predict the RUL of the lithium-ion battery and estimate its SOH. Besides, resampling is also an effective approach to restrain the particle degeneracy. But the introduction of the resampling will make the conventional PF suffer strongly from the particle impoverishment. Therefore, for improving this weakness, Dong et al. [12] used an improved PF known as the support vector regression particle filter, which improves the particle impoverishment, to estimate the SOH and predict the RUL of lithium-ion battery. Based on the former statement, it is noticed that the prediction algorithm of the electrolytic capacitors needs further research to extend the range of its application such as the prediction concerning the systems of non-linear and non-Gaussian, and needs to improve the prediction accuracy and efficiency.

Motivated by the above concerns, this paper aims to propose an adaptive and robust prediction method for the remaining useful life evaluation of electrolytic capacitors. In order to develop a suitable empirical model which possesses the high flexibility and adaptability for the degradation trend of the electrolytic capacitors, in this paper the empirical model is determined as the combination of the Verhulst model and the exponential model. Regarding the particle degeneracy, the method applies UKF to generate the suitable proposal distribution with a small variance for PF framework and then adopts the particle swarm optimization algorithm (PSO) to improve the particle impoverishment by refining the searching area of resampling. Moreover, in order to reduce the computational burden of the algorithm as much as possible, an optimization method that is adaptively adjusting the number of the samples is applied to calculate the least number of effective particles.

The rest of the paper is organized as follows. Section 2 presents the degradation mechanisms of electrolytic capacitors and describes the framework of the proposed method in detail. Section 3 shows the proposed prediction procedure and the performance of the proposed novel algorithm based on the real degradation data of electrolytic capacitors, and the comparison results of the conventional PF and the proposed method are also provided and analyzed. Finally, some conclusions are summarized in Section 4.

2. RUL prediction method for electrolytic capacitors

2.1. Capacitance degradation mechanism

Under a high voltage stress, electrolytic capacitors will undergo the performance degradation and then run to failure. Note that the electrolytic capacitors applied in this paper are all the "non-solid" aluminum electrolytic capacitors, whose electrolytic paper is permeated with the liquid electrolyte. There is no internal resistance in an ideal electrolytic capacitor. However, in practical applications, the liquid electrolyte, the plates of the electrolytic capacitor, and the aluminum oxide can generate a small equivalent series resistance (ESR). To obtain the capacitance value and ESR in a reasonable period of time, the electrolytic capacitors are always subject to a high voltage over-stress to accelerate the degradation. The electrolytic capacitor charges and discharges continuously and thus deteriorates gradually which is caused by the evaporation of electrolyte, the leakage current, and the increasing internal pressure.

When the DC voltage is applied to the discharged electrolytic capacitor, there is an initial surge of current in the electrolytic capacitor. The flow of current during the charge and discharge cycle will increase the internal temperature of the electrolytic capacitor. The higher temperature will make the electrolyte evaporate gradually. As a result, the ESR will increase and the capacitance will decrease. The periodic temperature cycle which is attributed to the charge and discharge of the electrolytic capacitor can cause the oxide layer to deteriorate. Although there is an insulating layer between the two plates, a small leakage current will still appear in the electrolytic capacitor, and the leakage current will be increasing with the degradation of the oxide layer. With the increase of the leakage current, ESR and the capacitance value will be affected as well. The third factor which is attributed to the electrolytic capacitor degradation is the increase of the pressure inside. The gas inside of the electrolytic capacitor can be generated by the rising of the internal temperature and the accelerated speed of the chemical reaction which occurs in the charging/discharging cycle, and the growing gas can increase the internal pressure of the electrolytic capacitor. Under such pressures, ESR and the capacitance value will surpass the failure threshold, then the electrolytic capacitor is considered to be completely failed. For more details of degradation mechanisms, interested readers also refer to [17,18,26].

2.2. Proposed method

In this section, this paper proposes a novel prediction method to estimate the unknown state and predict the RUL of the electrolytic capacitors. The proposed method applies PF as the framework of the prediction. The fundamental steps and principles of the conventional PF were detailed in [25]. The proposed framework of the novel method is shown in Fig. 1. With the degradation datasets of the electrolytic capacitors, the empirical model is firstly established and UKF is used to generate a proposal distribution with a small variance to improve the importance sampling step. After obtaining the importance weights of the particles, PSO is applied to refine the searching area to optimize particle impoverishment issue in resampling. In addition, to reduce the unnecessary calculation, a method of adjusting the particle number