Remaining useful life prediction for lithium-ion battery based on the particle filter considering temperature effect

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Abstract. Temperature would affect the degradation process of lithium-ion battery. Therefore, considering the influence of temperature, this paper proposes a method to predict the Remaining useful life (RUL) of the lithium-ion battery based on Arrhenius and double exponential model. And update the parameter by particle filter. Firstly, we establish a capacity degradation model with considering the influence of temperature, which is based on Arrhenius model and double exponential model. And then, in order to obtain the initial value of the parameters, we process the fitted lithium-ion battery degradation data. Next, we use the particle filter (PF) algorithm to update the model parameters to realize the capacity estimation and the RUL prediction. Finally, according to the experiment, we prove that the accuracy of the method proposed in this paper is better than that the method without considering the influence of temperature change. The result shows that the lithium-ion battery capacity degradation model established in this paper has great potential in the RUL prediction of the lithium-ion battery.

Keywords: Lithium-ion battery, RUL, PF algorithm, temperature.

1. Introduction
As the representative of new energy technology, Lithium-ion battery has become energy storage device in many fields because of its excellent characteristics [1], such as electric vehicles, personal electronic devices, military field and space field [2]. However, with the use of lithium-ion batteries, failure or even serious accidents may occur if the status of the lithium-ion battery is not monitored and prevented in time. For example, a Tesla electric vehicle caught fire while charging in Norway [3]. In order to prevent the occurrence of safety accidents caused by the failure of lithium-ion battery, the importance of prediction and health management (PHM) technology is increasingly prominent. Remaining Useful life (RUL) prediction is considered as one of the most pivotal parts in PHM [4,5]. Therefore, the problem of predicting the RUL of lithium-ion battery can be expressed by estimating the discharge capacity of lithium-ion battery. Thus, RUL of lithium-ion battery can be defined by the time when its capacity first exceeds a predefined failure threshold, which is usually set as 20%~30% of the rated capacity [6,7].

In the use of lithium-ion battery, due to the change of external environment and internal complex chemical reaction, it often works on a variable temperature condition which caused the degradation path of the battery irregular [8]. Because the temperature could affect the internal activity of lithium battery, the degradation capacity of lithium battery would change. Therefore, studying the influence of temperature on the deterioration law of lithium battery has important practical significance to improve
the reliability and safety of lithium battery. In view of this irregular degradation process, we can use the Particle Filter (PF) algorithm to predict the RUL of lithium-ion battery [6].

Considering the influence of temperature, this paper uses the Arrhenius model and double exponential model to establish the capacity degradation model and use the PF algorithm to predict RUL. In addition, the model is compared with the capacity degradation model without considering temperature, which shows that the model has better accuracy.

The specific structure of this paper is as follows:

Section 2 analyzes the degradation data of the lithium-ion battery and qualitatively obtains the influence law of temperature on its degradation process. In Section 3, we proposed the degradation model and update the parameters by PF algorithm. Then the RUL is predicted by degradation curve. And in Section 4, we provide a case to prove the effectiveness of the method that proposed in this paper.

2. Problem analysis

In order to explore the effect of temperature on the degradation process of lithium battery, we use the following the experiment data which come from CALCE. In this experiment, the degradation data under the temperature change condition are obtained from the single battery sample, which the capacity is 1.35 Ah, as shown in Fig 1.

![Figure 1. The experimental data.](image)

The experiment set the starting temperature as 25°C, then after 10 charge-discharge cycles, the temperature is raised 10°C. Moreover, every four large cycles is a whole temperature change cycle, to ensure the temperature working condition changes at 25°C ~ 55°C. And the relevant parameters of the lithium-ion battery is shown in Table 1.

| The type of battery | Battery capacity | Battery weight | Battery size | CC-CV |
|---------------------|------------------|----------------|--------------|-------|
| CX2 (LiCoO2)        | 1350mAh          | 28g            | 6.6 × 33.8 × 50mm | 2.7V-4.2V |

From the degradation data, it can be observed that temperature would affect the degradation rate and the capacity. At the same time, based on the experimental data, an obvious phenomenon was noticed. That is the sudden change of temperature would cause the sudden change of battery capacity, and with the increase of lithium battery recycling times, the sudden change of temperature is more and more obvious. This phenomenon shows that the effect of temperature on the degradation process is not constant, and the longer the service time, the greater the effect of temperature. Therefore, we explore the effect of temperature by established the degradation model. In the model, both temperature and cycle times should be considered to improve the accuracy and make the model more in line with the law reflected by the experimental phenomenon.
3. Degradation model and RUL method

A large number of studies show that Arrhenius model can well reflect the influence of temperature, and the double exponential model of empirical model can well fit the degradation data of lithium battery. After establishing the degradation model, we use the PF algorithm to establish the RUL method.

3.1. Establishment of the Degradation Model

The degradation model can be shown in Eq. (1)

$$ Q_i = e^{-\alpha T} \cdot (be^{ct} + de^{ft}) $$

Where $Q_i$ is the capacity at time $t_i$, $i = 1, 2, \ldots, n$, indicates the absolute temperature, $a$, $b$, $c$, $d$, $f$ represents the unknown parameters. Then we use the MATLAB function "cftool" to estimate the initial parameters. And we can gain the fitting results in Fig. 2.

![Figure 2. The model fitting results.](image)

From the Fig. 2, we can observe that the model in this paper can fit the capacity degradation data of lithium battery well which considering the temperature change. And the results of the parameters are in Table 2.

| $a$ | $b$ | $c$ | $d$ | $f$ |
|-----|-----|-----|-----|-----|
| 22.77 | $3.25 \times 10^{-6}$ | 0.0105 | 0.0547 | 0.00242 |

3.2. RUL method based on the PF algorithm

From the section 3.1, we established the model of the lithium-ion battery. And we use the method of function fitting to determine the initial value of parameters in the degradation model. Next, the parameters of the model will be updated by PF algorithm and RUL prediction will be performed. The PF algorithm is as follows:

Step1: Select the capacity degradation data of lithium battery.
Step2: Initialization. Set the particle number, process noise variance, measurement noise variance, failure threshold, prediction starting point and initial values of model parameters. In this paper, set the number of particles to 1000, set the failure threshold to 10.95Ah. And the initial values of model parameters are express as $a = 22.77$, $b = 3.25 \times 10^{-6}$, $c = 0.0105$, $d = 0.0547$, $f = 0.00242$.
Step3: According to the capacity degradation model, construct the state transition variance and measurement equation.
Where $\epsilon_a, \epsilon_b, \epsilon_c, \epsilon_d, \epsilon_f$, represent the noise, which are normally distributed and the mean is zeros the standard deviation is $\sigma_{\epsilon_a}^2, \sigma_{\epsilon_b}^2, \sigma_{\epsilon_c}^2, \sigma_{\epsilon_d}^2, \sigma_{\epsilon_f}^2$, respectively. $Q_i$ represents the capacity at the $t_i$ time.

Step 4: Model parameter updating. By setting the training set and updating the parameters of PF algorithm, we can obtain capacity estimation of lithium-ion battery.

Step 5: Obtain results of the RUL. The service life is predicted by the capacity corresponding to the cycle times of the battery in the model.

In the above 5 steps, describe the whole process of updating model parameters by PF algorithm in detail. The algorithm mainly sets the initial value of the error and updates the parameter values in real time with the increase of monitoring data. Next, we will illustrate the effectiveness of the proposed method through a practical case.

### 4. Comparison of experimental results

In this section, we use a practical example to illustrate the effectiveness of the method proposed in this paper. And, the degradation data of the lithium-ion battery are shown in Fig.1.

We denote the method developed in this paper as the M1 which is under the temperature changing condition. And the M2 represent the prediction method that not considering the influence of temperature change. And the set the 70% of initial battery capacity as the failure life threshold. Finally, we use relative error (RE) for a comparative study to illustrate the accuracy.

$$RE_i = \text{Prediction}_i - \text{Real}_i$$  \hspace{1cm} (4)

The specific experimental steps are as follows:

1. Set the predict starting point as 500 and 600, then use the PF algorithm to predict the RUL of the lithium-ion battery based on the model.

2. Summarized the results as shown in Table 3. Perform 50 repetitions and summarize the results as shown in Table 3.

Then, by setting the predict starting point as 500 and 600, calculate the average value of REs, and the results are shown in Table 3.
Figure 3. The results of the previous point 600 for an experiment.

Table 3. Forecast results.

| Method | previous point | The actual RUL | The prediction RUL | RE |
|--------|----------------|----------------|--------------------|----|
| M1     | 500            | 855            | 834.3              | 20.7 |
|        | 600            |                | 842.5              | 12.5 |
| M2     | 500            | 769.6          | 769.6              | 85.4 |
|        | 600            |                | 791.2              | 63.8 |

Table 3 shows that the RUL of M1 are 834.3 and 842.5 cycles, and the REs are 20.7 and 12.5 cycles, while the life prediction of M2 are 769.6 and 791.2 cycles, and the REs are 85.4 and 63.8 cycles. These results show that the RUL prediction accuracy of the method proposed in this paper is higher than that of the method which is not considering the effect of the temperature.

5. Conclusions

In order to improve the safety and reliability of lithium battery working in temperature changing condition, this paper proposed a RUL prediction method of lithium battery. This method is based on Arrhenius model and double exponential model to establish the degradation model of lithium battery. Then, we use the function “cftool” in MATLAB to estimate the initial parameters of the model. Next, we use the PF algorithm update the values of each parameter online and map the predicted value of its remaining life by estimating the capacity of lithium battery. Finally, an effectiveness is given to verify the effectiveness of this method, which shows that this method has better accuracy than the prediction method without considering the influence of temperature.

In practical use, internal temperature of the lithium-ion battery is difficult to measure. And this paper only consider the temperature constancy of the working environment of the lithium-ion, but its internal temperature is not considered. Therefore, how to measure the internal temperature of lithium-ion battery remains to be further studied.

References

[1] Xu F, Yang F, Fei Z, et al. Life prediction of lithium-ion batteries based on stacked denoising autoencoders[J]. Reliability Engineering & System Safety, 2021, 208.

[2] Han X, Feng X, Ouyang M, et al. A Comparative Study of Charging Voltage Curve Analysis and State of Health Estimation of Lithium-Ion Batteries in Electric Vehicle[J]. Automotive Innovation, 2019, 2(4):263-275.

[3] Qi C, Zhu Y-L, Gao F, et al. Safety analysis of lithium-ion battery by rheology-mutation theory coupling with fault tree method[J]. Journal of Loss Prevention in the Process Industries, 2017, 49:603-611.

[4] Xu X, Yu C, Tang S, et al. Remaining Useful Life Prediction of Lithium-Ion Batteries Based on Wiener Processes with Considering the Relaxation Effect[J]. Energies, 2019, 12(9).
[5] Tang S, Yu C, Wang X, et al. Remaining Useful Life Prediction of Lithium-Ion Batteries Based on the Wiener Process with Measurement Error[J]. Energies, 2014, 7(2):520-547.

[6] Duong P L T, Raghavan N. Heuristic Kalman optimized particle filter for remaining useful life prediction of lithium-ion battery[J]. Microelectronics Reliability, 2018, 81:232-243.

[7] Xu X, Tang S, Yu C, et al. Remaining Useful Life Prediction of Lithium-ion Batteries Based on Wiener Process Under Time-Varying Temperature Condition[J]. Reliability Engineering & System Safety, 2021, 214.

[8] Chang W, Bommier C, Fair T, et al. Understanding Adverse Effects of Temperature Shifts on Lithium-Ion Batteries: An Operando Acoustic Study[J]. Journal of The Electrochemical Society, 2020, 167(9).