Remaining Useful Life Predictions in Lithium-ion Battery under Composite Condition

Yejin Kim[1], Jongsoo Lee[1]

[1]*School of Mechanical Engineering, Yonsei University, Seoul, 120-749, Korea*

yjk9199@yonsei.ac.kr
jleej@ yonsei.ac.kr

ABSTRACT

In these days, there is a tendency that research of Prognostics and Health Management (PHM) of lithium-ion battery that prevent accidents in advance by predicting the Remaining Useful Life (RUL). However, there is a difficulty in battery evaluation for composite condition of an operating conditions and a storage conditions, due to the time consuming. Research on the RUL of lithium-ion battery in composite condition are progressing by combining an operating condition and a storage condition. Conventional method such as Miner's Rule may not fully meet the needs of battery evaluation for RUL. Because it does not take into account overloads caused by a variable amplitude loading history. In order to solve the problem of accurately predicting the RUL of lithium-ion battery, two approaches applied to predicting the RUL of lithium-ion battery. We demonstrate the usefulness of two proposed methods by comparing with real-data of composite condition.

1. INTRODUCTION

Concern over bio-energy along with environmental matters is increasing recently with accentuated importance of battery that can store and supply new energy accordingly. However, unlike 12 V plumbate supplementary battery which needs periodic exchange, lithium-ion battery with high voltage for green car requires durability same with that of car. Falling under a certain capacity compared to initial capacity is considered failure in lithium-ion battery requiring exchange. Therefore, researches to distinguish and predict Remaining Useful Life (RUL) of batter in advance are conducted actively with concern over importance of battery failure prediction (Cho et al, 2010; Goeble et al, 2008; Arenas et al, 2015; Zackrisson et al, 2010; Xiong et al, 2013; Jung et al, 2010).

Nonetheless, we have many hardships in evaluations and tests due to spent time in combined durability of cycle and storage, which are general car environmental conditions. Durability life model based on many electrochemistry which has been developed as a way to predict the life expectancy of battery being used currently does not accord a little change in battery chemical formation with much spending time, leading to cases where utilization is not fully achieved because of many doubts in accuracy and actual usability. Thus, current tendency is to predict durability as a way to combine combined durability of storage condition and cycle condition rather than model based on battery chemistry. To improve and overcome matters over reliability and stability of lithium-ion battery that is not caused in initial phase of usage, hence, studies were conducted after selecting prognostics and health monitoring. This can predict failures in advance by predicting Remaining Useful Life (RUL) of lithium-ion battery increasing reliability of parts, and it is possible to save cost in maintenance and repair (Choi et al, 2000; Kim et al, 2009; Sim et al, 2013; Kim et al, 2012).

In current studies, we use Miner's Rule as an estimation model for battery combined durability. This is advantageous in that it can predict life expectancy of lithium-ion battery even upon occurrence of different stress factor. But it is disadvantageous in that it cannot consider interaction effect between different stress, so we intend to provide basic data that can accurately evaluate combined durability of lithium-ion battery based on test data of lithium-ion obtained from cycle condition and storage condition as well as presenting new approaches to solve problems of current Miner's Rule.

Figure 1. Lithium-ion Battery test device

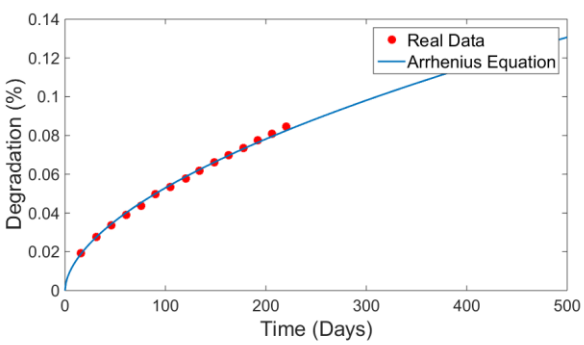

Figure 2. Arrhenius Equation and Real Data at 25℃

2. BATTERY MODELING

2.1. Organization of test devises

This study performed direct charging or discharging experiment show relation between number of times it was charged and discharged and capacity degradation of lithium-ion battery. Figure 1 shows testing device which performed tests and they are charger/discharger that can enable long term characteristic test of medium and large sized battery for electric car (PNE solution., 2016).

This is used for experimenting life expectancy and features of battery upon battery development. The experiment was done keeping ambient temperature stable in 3 times under the same conditions regarding the same battery model. We permitted stable current range and measured capacity of lithium-ion battery according to the number of times they were charged and discharged to test it. Data is shown in Figure 2 accordingly.

Since battery of same models was used under same conditions in this experiment, 3 experiments showed almost same result value.

2.2. Arrhenius modeling

Lithium-ion battery evaluation tests are needed basic model for evaluating the life using the initial experimental data only, because it takes a long time. So we estimate the data, beyond the original observation range by using extrapolation. In this study, we use Arrhenius Equation. Arrhenius Equation is the method used for life expectancy in cycle and storage condition in this study. Arrhenius Equation is an equation showing relation between reacting speed and temperature being represented in Eq. (1).

$$\mathrm{k} = \mathrm{Aexp}\left(\frac{-E_a}{RT}\right) \quad (1)$$

To show relation between number of times it was charged/discharged and capacity of lithium-ion battery, this study used Eq. (2) which follows power series function regarding number of times charged and discharged and Arrhenius Equation that transformed current Arrhenius Equation in this research (Bloom et al, 2001; Han et al, 2014; Ramadass et al, 2003; Ma et al, 2013).

$$\mathrm{Q} = \mathrm{Aexp}\left(\frac{-E_a}{RT}\right) t^z \quad (2)$$

Q : Capacity loss (%)

A : Pre-exponential Factor

E_a : Activation Energy in J

R : Gas Constant

T : Absolute Temperature

t : Time (Days)

z : Exponent of Time

For the experiment was done keeping ambient temperature stable, $\exp\left(\frac{-E_a}{RT}\right)$ was designated as a constant value changing by experimental conditions with constant A. Values of A, $\exp\left(\frac{-E_a}{RT}\right)$, z used least square technique to extract the value where r^2 is the biggest. Actual data value and approximation curves were shown Figure 2 similar with r^2 value 0.9982.

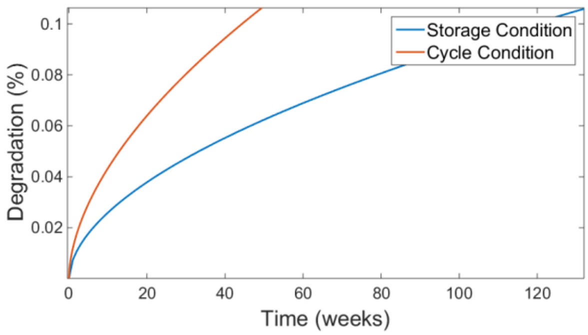

Figure 3. Curves according to the conditions

This was done under temperature condition of 25℃.

3. COMBINED METHOD

This study intend to expect life expectancy of lithium-ion battery according to EOL(End of Life) and user conditions combining data of two conditions in cycle condition and storage condition. Life expectancy was predicted in a way that combined durability of cycle condition and storage condition combined.

3.1. Miner's Rule

Current study about life expectancy was done using Miner's Rule under combined conditions. Miner's Rule is shown in Eq. (3). It is possible to combine cumulative contributory portion by each constituent with different cycle under changing conditions (Feinberg et al, 2000).

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} = \frac{1}{N} \qquad (n_1 + n_2 = 1) \tag{3}$$

N : Battery Life at EOL in Composite Condition

N_1 : Battery Life at EOL in Cycle Condition

N_2 : Battery Life at EOL in Storage Condition

n_1 : Ratio of Cycle during lithium-ion battery usage

n_2 : Ratio of Storage during lithium-ion battery usage

Eq. (3) is combined with storage condition and cycle condition, Eq. (4) summarizes life expectancy of battery when lithium-ion battery reaches EOL.

$$\text{Total Life at E\% Degradation} = \frac{1}{\frac{Cycle\ Life\ Portion}{Cycle\ Life\ at\ E\%} + \frac{Storage\ Life\ Portion}{Storage\ Life\ at\ E\%}} \tag{4}$$

Nevertheless, it is a possible law to be used when expecting life expectancy within the same condition. There exists limitation, therefore, to use it under changing conditions with different curve, not with same curve like Figure 3. It is disadvantageous in that Miner's Rule cannot consider influence by prior conditions and interaction effect accordingly when condition 1 is changing to condition 2 giving combined conditions.

As a result, we expect long life expectancy longer than actual one if we calculate life expectancy using Miner's Rule.

3.2. Predict Life expectancy under combined conditions

In this study, we try to improve the matters that usage of current Miner's Rule renders us longer life expectancy than actual ones. Aside from Miner's Rule, we suggest new approaches in 2 types of method, to obtain accuracy in life prediction of lithium-ion battery through this.

3.2.1. New Approach Method 1

We present method to predict fatigue life expectancy to solve matters that current Miner's Rule cannot consider interaction effect between conditions and consider phenomena where influence about these conditions gradually get cumulative in lithium-ion battery. Ye Duyi, Wang Zhenlin presented modified Miner's Rule that can consider interaction effect by phenomenon with changing conditions. This was applied in life expectancy method of lithium-ion battery naming this method 1. This law is based on internal energy and the cumulative amount of damage in structures by load. This law always owns positive numbers upon irreversible transformations with always increasing internal energy, and it is advantageous in that it is suitable to be used for evaluation towards procedures where damage is cumulative. In method 1, Eq. (5) shows amount of cumulative damage affecting on lithium-ion battery by cycle condition (Lv et al, 2015; Marano et al, 2009; Kim et al, 2002).

$$D_1 = -\frac{D_{(N_1-1)}}{\ln N_1} \ln\left(1 - \frac{n_1}{N_1}\right) \tag{5}$$

Likewise, Eq. (6) shows amount of cumulative damage E on lithium-ion battery by storage condition.

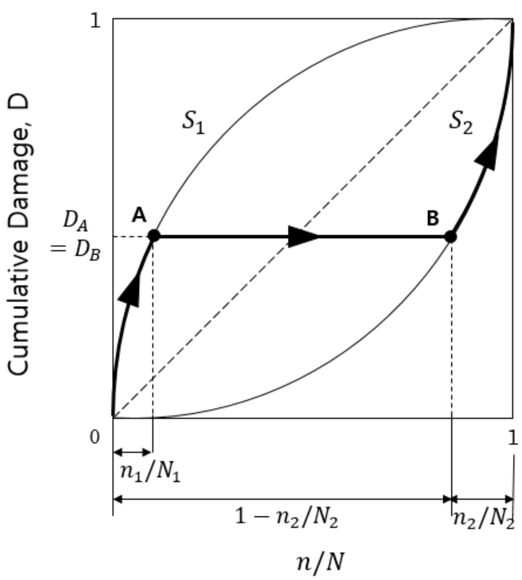

Figure 4. Cumulative damage according to $\mathbf{n/N}$

$$D_2 = -\frac{D_{(N_2-1)}}{\ln N_2}\ln(1-\frac{n_2}{N_2}) \tag{6}$$

Cycle condition affects in the degree of n_1 until lithium-ion battery is deteriorated while affecting in the degree of $1 - n_1 = n_2{}'$ in storage condition. Eq. (6) summarized accordingly is shown in Eq. (7).

$$D_2 = -\frac{D_{(N_2-1)}}{\ln N_2}\ln(\frac{n_2{}'}{N_2}) \tag{7}$$

Since amount of cumulative damage D_1 by cycle condition and amount of cumulative damage D_2 by storage condition are same, Eq. (8) shows summary of this.

$$\frac{n_1}{N_1} + \left(\frac{n_2{}'}{N_2}\right)^{\frac{D_{(N_2-1)}}{D_{(N_1-1)}}\frac{\ln N_1}{\ln N_2}} = 1 \tag{8}$$

Eq. (8) $D_{(N_{f_2}-1)}/D_{(N_{f_1}-1)}$ is expressed as follows.

$$\frac{D_{(N_2-1)}}{D_{(N_1-1)}} \approx 1 \tag{9}$$

Finally, Eq. (8), (9) can get Eq. (10).

$$\frac{n_1}{N_1} + \left(\frac{n_2{}'}{N_2}\right)^{\frac{\ln N_1}{\ln N_2}} = 1 \tag{10}$$

When we say N is the life expectancy until lithium-ion battery is deteriorated until EOL, Eq. (10) can be modified to get Eq. (11).

$$\frac{n_2 \times N}{N_2} = \left(1 - \frac{n_1 \times N}{N_1}\right)^{\frac{\ln N_2}{\ln N_1}} \tag{11}$$

3.2.2. New Approach Method 2

D. S. Kim, J. K. Kim suggested non-linear cumulative damage law where amount of cumulative damage D is supposed as exponential function form of n/N to complement weakness of Miner's Rule. D. S. Kim, J. K. Kim evaluated amount of cumulative damage D with Eq. (12) noticing degradation pattern of residual stiffness and non-linear degradation tendency according to load repetition (Kim et al, 1996)

$$\mathrm{D} = \frac{E_0 - E_{sn}}{E_0 - E_{sf}} \tag{12}$$

Here, E_0 is an initial elastic modulus while E_{sf} is a secant coefficient, E_{sn} is a secant coefficient after n cycle. Figure 4 shows damage curve regarding amount of cumulative fatigue damage D under combined load. With Eq. (13) that takes n/N for its root, S_1, S_2, damage curve regarding amount of cumulative fatigue damage D, was defined. Under first load, cumulative damage is accumulated until point A during n_1 cycle along damage curve by S_1. Next, when second load is put, point A moves to point B which owns same amount of cumulative damage. From point B, cumulative damage is accumulated along damage curve S_2, causing final damage in point (1, 1).

$$D_i = \propto_i \left(\frac{n_i}{N_i}\right)^3 + \beta_i \left(\frac{n_i}{N_i}\right)^2 + \gamma_i \left(\frac{n_i}{N_i}\right) + \omega_i \tag{13}$$

In this procedure, $D_A = D_B$, exponent correlation between D and n/N was supposed Eq. (14).

$$\left(1 - \frac{n_1}{N_1}\right)^{f(S_1)} = \left(\frac{n_2}{N_2}\right)^{f(S_2)} \tag{14}$$

Table 1. Life expectancy of Lithium-ion Battery according to combined method

Temperature	Charging Type	Cycle ratio/ Storage ratio	Real Data (yr.)	Miner's Rule (yr.)	Method 1 (yr.)	Method 2 (yr.)
25	Quick Charging	10/90	12.36	12.89	12.05	12.20
		15/85	6.44	8.98	7.89	7.63
	Slow Charging	32/68	9.01	9.28	8.80	9.17
		20/80	5.38	6.72	5.93	5.54
		33/67	4.44	5.05	4.48	4.21
		50/50	2.82	3.82	3.44	3.07
		70/30	2.61	2.96	2.75	2.36

Table 2. RMSE according to combined method

	Miner's Rule	Method 1	Method 2
RMSE	1.20	0.64	0.48

Eq. (13) and Eq. (14) were applied in method of life expectancy of lithium-ion battery to name it method 2.

By summarizing based on amount of ith cumulative damage in Eq. (12), Eq. (15) is shown.

$$D_i = \frac{(Capacity\ loss_{initial})_i - (Capacity\ loss_{current})_i}{(Capacity\ loss_{initial})_i - (Capacity\ loss_{final})_i} \quad (15)$$

$$D_{Cycle} = \propto_{Cycle}\left(1 - \frac{n_{Cycle} \times N}{N_{Cycle}}\right)^3 + \beta_{Cycle}\left(1 - \frac{n_{Cycle} \times N}{N_{Cycle}}\right)^2 + \gamma_{Cycle}\left(1 - \frac{n_{Cycle} \times N}{N_{Cycle}}\right) + \omega_{Cycle} \quad (16)$$

From this procedure, battery life expectancy (N) when reaching EOL at combined durability can be obtained from Eq. (16), (17), (18).

$$D_{Calendar} = \propto_{Calendar}\left(\frac{n_{Calendar} \times N}{N_{Calendar}}\right)^3 + \beta_{Calendar}\left(\frac{n_{Calendar} \times N}{N_{Calendar}}\right)^2 + \gamma_{Calendar}\left(\frac{n_{Calendar} \times N}{N_{Calendar}}\right) + \omega_{Calendar} \quad (17)$$

$$D_{Cycle} = D_{Calendar} \quad (18)$$

When combining cycle condition and storage condition, we summarized result value where predicted result for combined life expectancy of lithium-ion battery is compared to the result value of life expectancy predicted through method 1 and 2, Miner's Rule and actual data value. Moreover, with RMSE (Root Mean Square Error) we showed life expectancy between estimated life expectancy and actual one and through this, we verified validity of method 1 and 2 through this. RMSE value with predicted result value of life expectancy through three methods and actual data, predicted result for combined life expectancy of lithium-ion battery were summarized in Table 2. In Table 2, we confirmed RMSE to be 1.20 as a way to predict life expectancy through Miner's Rule while checking significant decrease between RMSE 0.64 and 0.48 of method 1 and 2 which are new approaches.

4. Conclusion

Through this study, we predicted life expectancy of lithium-ion battery according to combined durability condition. Current Miner's Rule presented two new approaches to solve the problem.

(1) We predicted life expectancy of lithium-ion battery with modified Miner's Rule which can consider interaction effect by phenomena with changing conditions based on amount of damage and cumulative internal energy. Compared to Miner's Rule, strength decrease was considered, but it was not considered enough more than actuality regarding wide ranges of conditions with wide charging ranges.

(2) Paying attention to tendency of non-linear degradation and degradation pattern of residual stiffness as to load repetition, we predicted life expectancy of lithium-ion battery according to combined durability condition with approaches considering amount of cumulative damage D. There was error occurrence with actual value since we could not consider errors enough in the process of making approximation curve with third degree polynomial regarding test data.

By prediction of life expectancy through new approaches, we confirmed we could improve problems of current Miner's Rule and increase accuracy in predicting life expectancy of lithium-ion battery under combined durability condition.

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BIOGRAPHIES

Yejin Kim is Currently M.S. in Mechanical Engineering at Yonsei University, Korea.

Jongsoo Lee received B.S. in Mechanical Engineering at Yonsei University, Korea in 1988 and Ph.D. in Mechanical Engineering at Rensselaer Polytechnic Institute, Troy, NY in 1996. After a research associate at Rensselaer Rotorcraft Technology Center, he is a professor of Mechanical Engineering at Yonsei University. His research interests include multidisciplinary/multi-physics/multi-scale design optimization and reliability-based robust engineering design with applications to structures, structural dynamics, fluid-structure interactions and flow induced noise and vibration problems.