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Ni-MH Battery Voltage Statistical Analysis in Lifetime Cycle Experiment

by

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Abstract

Nickel-metal hydride (Ni-MH) batteries are widely installed for traction energy storage in electrical prime movers. A battery deteriorates due to chemical reactions has a cycle and preservation life. The battery focused on Ni-MH battery which is widely used for traction energy storage in hybrid electric vehicles (HEVs). The verification batteries are two types which are the most popular type of AB5 alloy structure and the usability improvement type of a super lattice one. This study investigates the statistical method applied to the battery terminal voltage in cycle mode experience, which can be verified the battery deterioration state in the progress of experiment cycles. The battery examination load condition drives the Japanese JC08 test cycle mode to estimate a real world usage. The study final object is to establish a method to verify the battery state of health (SOH) for on-board operating conditions.

Keywords: Automobile, Battery, Measurement, Voltage, Analysis

1. Introduction

A traction battery installed on Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) have a deterioration of life with chemical reactions. This study investigates a possibility extent that a battery terminal voltage characteristic represents the battery deterioration level. A battery is focused on a Nickel-metal hydride (Ni-MH) battery which is used widely as traction energy storage in electric prime movers. Major battery deterioration parameters are enumerated a battery state of charge (SOC) which shows the battery charged amount, and a battery temperature[1]. Battery deterioration level can be verified by a discharge capacity test and a high rate discharge test, which are both precise measurements on a laboratory scale condition. And another method, the battery deterioration level can be detected easily to measure the battery AC impedance on a laboratory scale condition [2), 3)]. The battery AC impedance characteristic is applicable to investigate the deterioration of some type of battery and the other type of battery is necessary to establish an applicable method. We examined the verification method of the battery terminal voltage of cycle mode experience which is the subject of interest in this study.

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2. Experimental method

2.1 *Battery*

Experimental batteries are commercial model of Ni-MH secondary batteries in two types and each three samples. One is the most popular AB5 alloy type and the other is a super lattice alloy type. Herewith, the AB5 alloy type is called “AB5” in short and the super lattice alloy type is called “SL” in short. The specific battery capacity is 1900mAh both AB5 alloy type and SL alloy type. The AB5 battery has the name of EVOLTA (type; HHR-3MWS) manufactured by Panasonic Co., Ltd. The SL battery has the name of Eneloop (type; HR-3UTGB) also manufactured by Panasonic Co., Ltd. The examination is carried out with the brand-new battery after activation under both charged and discharged within 10 cycles.

2.2 *Theory*

The battery terminal voltage of cycle mode experience is verified with a method of Mahalanobis distance analysis condition [4) to 8)]. The Mahalanobis distance analysis is as follows; Data $u_{i,j}$ is defined both a number of events i $(i=1$ to $n)$ and of components j $(j=1$ to $m)$. In a component of the basic standard group, a means of the events is μ_j, a variance of the events is σ_j^{2}, Data $u_{i,j}$ is written at the unit space by standardizing $U_{i,j}$.

$$v_{j1,j2} = \frac{1}{n}\sum_{i=1}^{n}(U_{i,j1} - \overline{U}_{j1})\cdot(U_{i,j2} - \overline{U}_{j2}) \tag{1}$$

The basic standard group consists of a number of components. A covariance V is written between components.

$$V = \begin{bmatrix} 1 & v_{1,2} & \cdots & v_{1,m} \\ v_{1,2} & 1 & \cdots & v_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ v_{1,m} & v_{2,m} & \cdots & 1 \end{bmatrix} \tag{2}$$

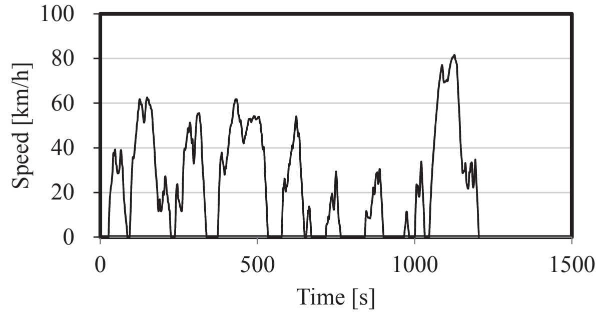
$$D = \sqrt{\frac{1}{m}\begin{bmatrix} X_{1,1} & \cdots & X_{1,m} \\ \vdots & \ddots & \vdots \\ X_{k,1} & \cdots & X_{k,m} \end{bmatrix}\cdot V^{-1}\cdot\begin{bmatrix} X_{1,1} & \cdots & X_{1,m} \\ \vdots & \ddots & \vdots \\ X_{k,1} & \cdots & X_{k,m} \end{bmatrix}^{t}} \tag{3}$$

Mahalanobis distance $d_{i,j}$ to a data $x_{i,j}$ of verification group is determined to Eq. (3) matrix. The distance $d_{i,j}$ and the data $x_{i,j}$ is defined with both a number of events i $(i=1\ to\ k)$ and a number of components j $(j=1\ to\ m)$. Herewith the Mahalanobis distance matrix D is applied the following diagonal matrix elements to the verification. And the data $x_{i,j}$ is standardizing $X_{i,j}$ with the unit space shown in Eq. (4).

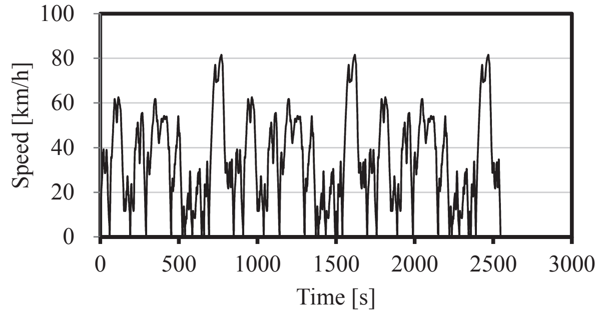
$$D = \begin{bmatrix} d_{1,1} & - & \cdots & - \\ - & d_{2,2} & \cdots & - \\ \vdots & \vdots & \ddots & \vdots \\ - & - & \cdots & d_{k,k} \end{bmatrix}, \quad X_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^{\,2}}} \tag{4}$$

2.3 *Method*

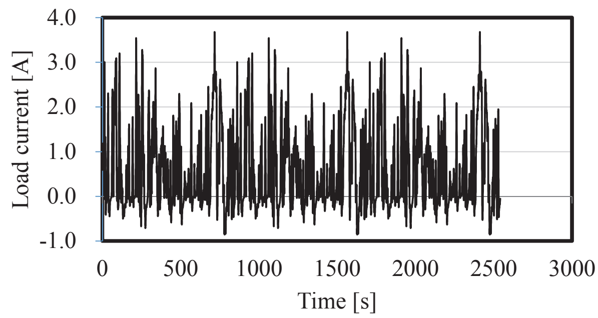
The experimental test condition is as follows; a charge-discharge electrical load to the experimental battery is set by load control unit (type; HJ0610SD8Y) manufactured by Hokuto Denko Co., Ltd. The experimental battery temperature is set in a thermostatic chamber (type; LU-113) manufactured by Espec Co., Ltd. The experimental battery AC impedance response with sweeping frequency is measured by a chemical impedance analyzer (type; IM3590) manufactured by Hioki Co., Ltd. The battery cycle examination load is applied on the basis of JC08 mode (the verification mode for vehicle fuel consumption and exhaust gas emission certified by Japanese government). The JC08 mode consists of zero speed part which simulates an engine idling condition. The verification load profile is shown in Fig. 1 which repeats three times of the JC08 load to maintain the currently specified range from 60% SOC to 40% SOC[9) to 12)].



(a) JC08 mode



(b) Examination mode profile
(Three cycles of JC08 mode, deleted zero speed data)



(c) Examination load profile

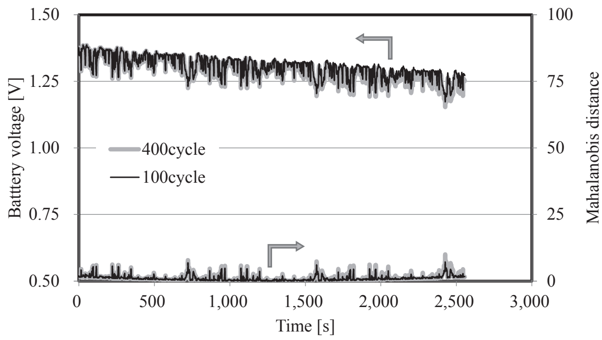
Fig. 1 Examination cycle profile of experimental battery

The actual load current profile scales down to the experimental battery load rate. The battery experiment one cycle consists of JC08 load for 20% discharge and a load back to 20% charge with a constant current 950mA (0.5C). The experimental battery AC impedance measurement has done when the experimental cycle to reach in each check point cycle. The measurement has carried out after the following conditioning. The experimental battery is charged to a full capacity level and then preserved for 12 hours to reach a steady condition of the battery. The experimental battery connected to a measurement wire harness where is attached to solder pieces of metal which prevents a voltage drop of the contact resistance. This is because the battery impedance is so small which level is a few milli-ohm, and necessary to reduce any ohmic loss during the battery AC impedance measurement. The experimental battery AC impedance measurement connects the measurement wires, which connected both battery terminal with solder, insert a test fixture (type; IM3590) manufactured by Hioki Co., Ltd. The measurement has taken three times to acquire the appropriate data. The battery AC impedance response is measured at a different frequency to apply the battery. The AC impedance measurement is done from 1000Hz to 0.1Hz, on the frequency range from 1000Hz to 100Hz in each 100Hz step, on the frequency range from 100Hz to 10Hz in each 10Hz step, on the frequency range from 10Hz to 1Hz in each 1Hz step and on the frequency range from 1Hz to 0.1Hz in each 0.1Hz step. The results of the AC impedance measurement reveals both battery impedance components of the real part Z’ and of the imaginary part Z”. After the measurement, the experimental battery is discharged with a constant current 950mA (0.5C) to an empty capacity level 1.0V. Then the experimental battery is charged with a constant current 950mA (0.5C) for two hours to a full capacity level. A battery voltage curve nearly traces CC-CV (constant current – constant voltage) curve of standard charge method.

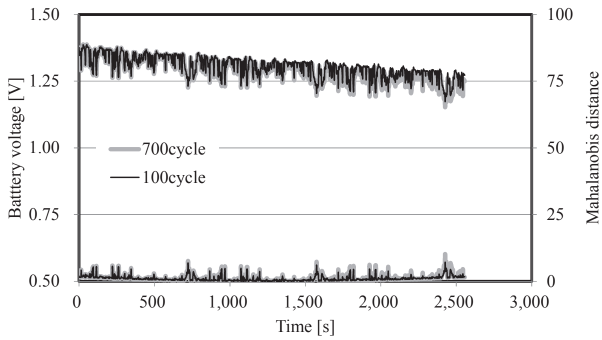
3. Experimental result

3.1 *Experimental battery terminal voltage*

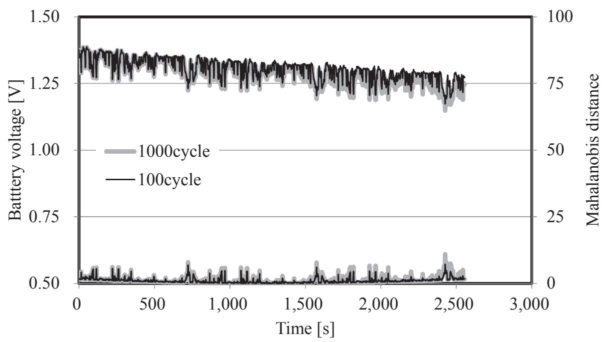
Figures 2 to 7 have two scales of vertical axis which are a battery terminal voltage in the left side and Mahalanobis distance concerned with the battery terminal voltage in the right side. The battery terminal voltage of 100th cycle mode experience is the reference tracking line of the battery terminal voltage which shown in the black solid thin line. The battery terminal voltage of verification cycle mode experience is over the reference tracking line plotted on the same upper side figure, which shown in the gray solid thick line. The verification load is shown in Fig. 1 which repeats three times of JC08 cycle mode without zero speed data, maintaining the currently specified range from 60% SOC to 40% SOC. The battery terminal voltage gradually decreases along with the declining of battery SOC. The Mahalanobis distance is also shown on the bottom side figure in Fig.2 where the standard feature group of the battery terminal voltage of the 100th cycle mode experience which shown in the black solid thin line, to the verification cycle mode which shown in the gray solid thick line. The drop range of the battery terminal voltage grows larger along with the experiment cycle increase which can be also recognized of the Mahalanobis distance.



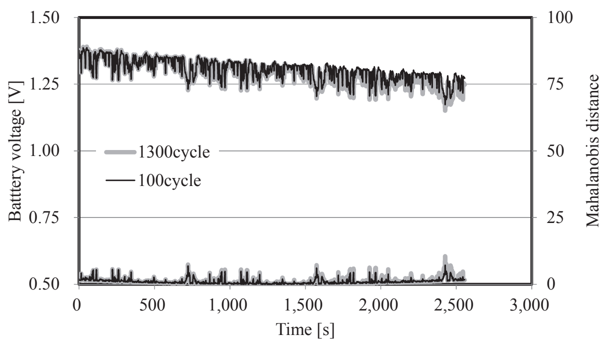
(a) 400 cycle



(b) 700 cycle

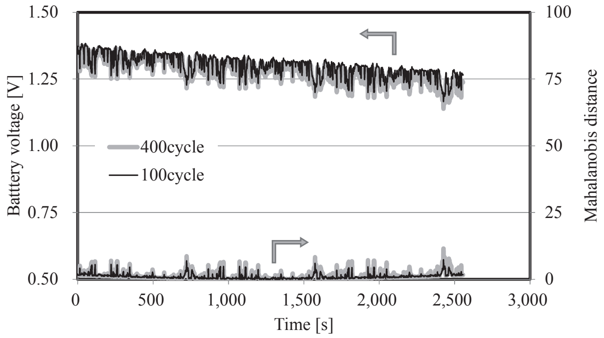


(c) 1000 cycle

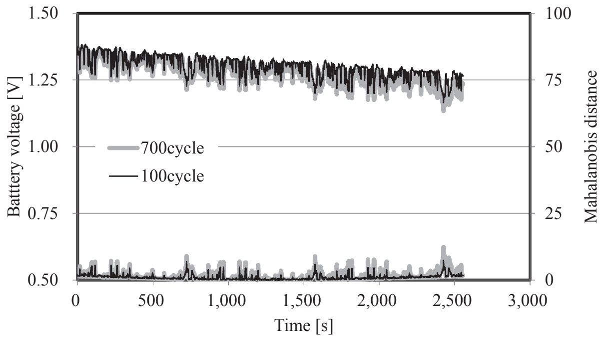


(d) 1300 cycle

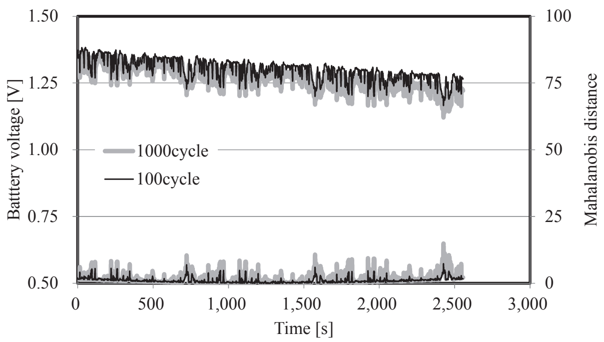
Fig. 2 Battery voltage and Mahalanobis distance
(No.1 experiment sample, SL type battery)



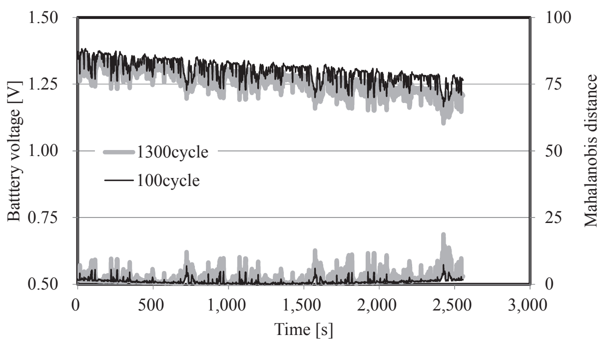
(a) 400 cycle



(b) 700 cycle

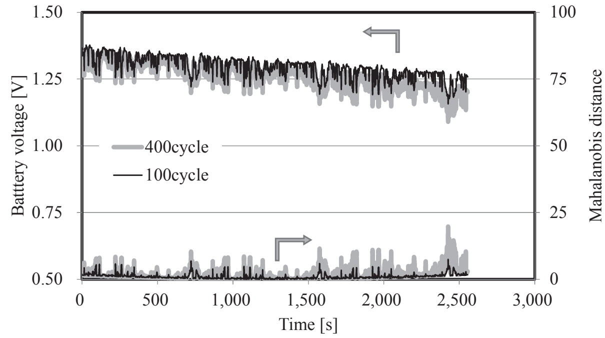


(c) 1000 cycle

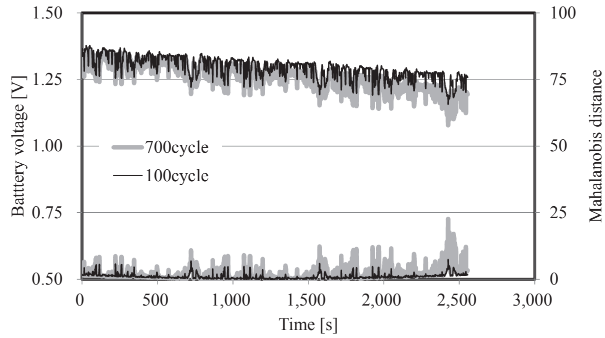


(d) 1300 cycle

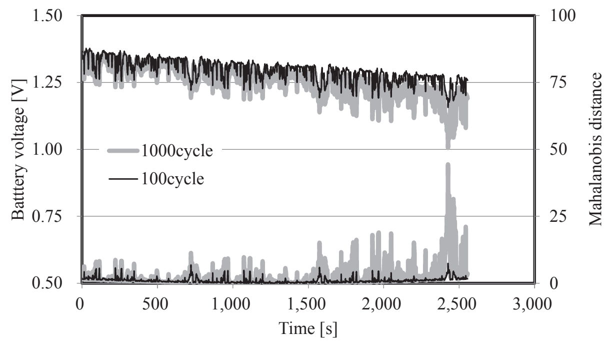
Fig. 3 Battery voltage and Mahalanobis distance
(No.2 experiment sample, SL type battery)



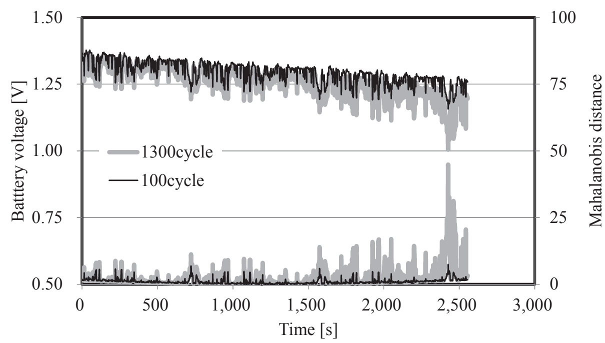
(a) 400 cycle



(b) 700 cycle

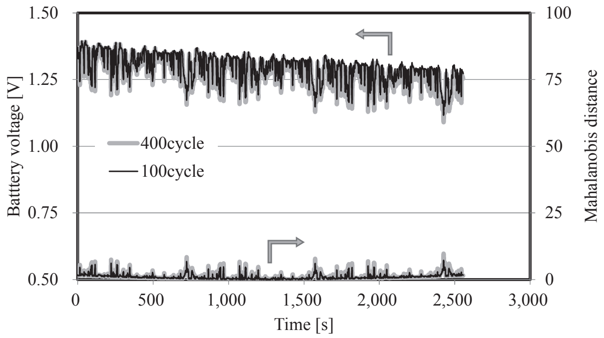


(c) 1000 cycle

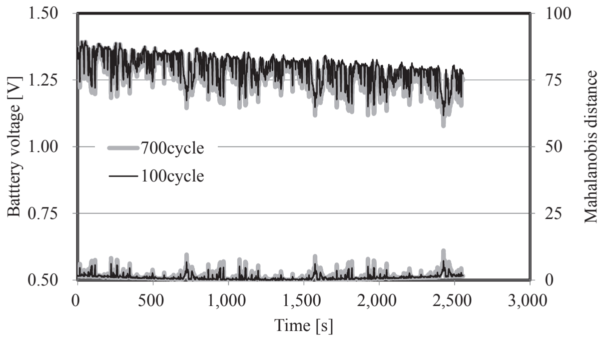


(d) 1300 cycle

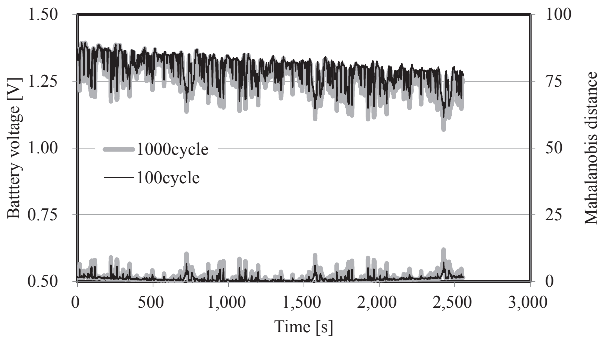
Fig. 4 Battery voltage and Mahalanobis distance
(No.3 experiment sample, SL type battery)



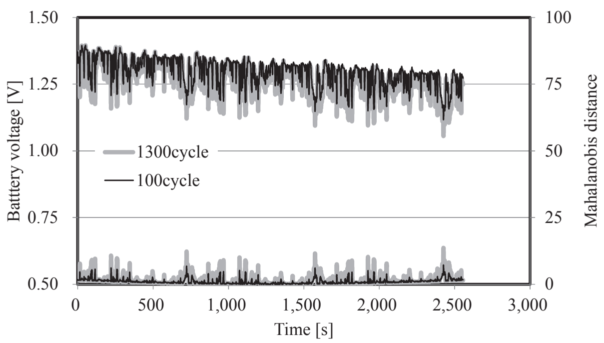
(a) 400 cycle



(b) 700 cycle

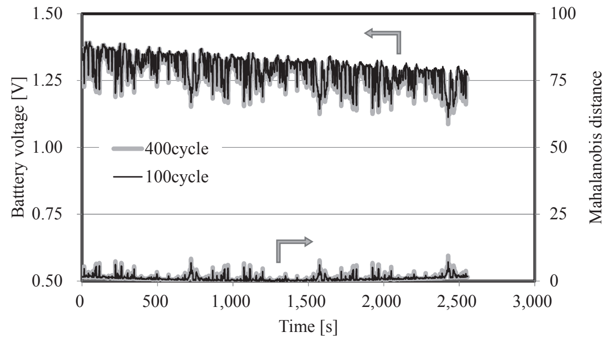


(c) 1000 cycle

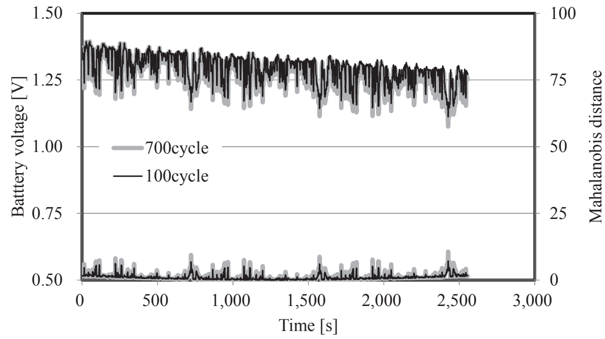


(d) 1300 cycle

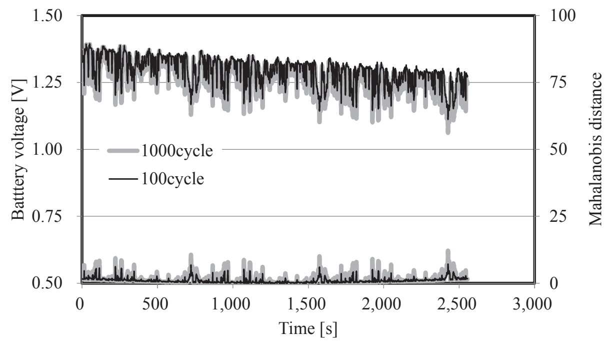
Fig. 5 Battery voltage and Mahalanobis distance
(No.1 experiment sample, AB5 type battery)



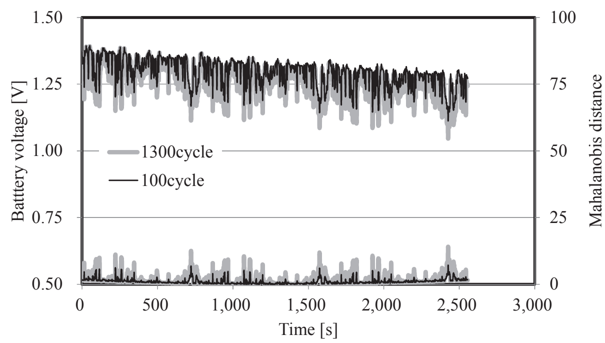
(a) 400 cycle



(b) 700 cycle

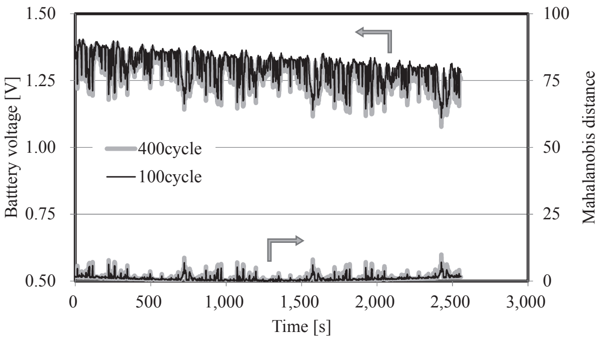


(c) 1000 cycle

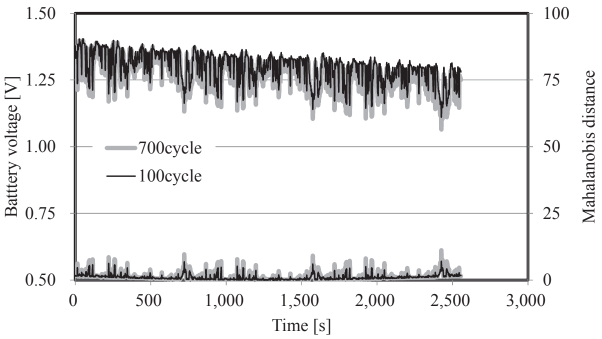


(d) 1300 cycle

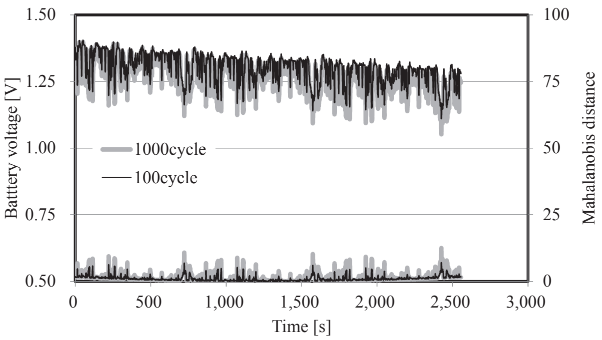
Fig. 6 Battery voltage and Mahalanobis distance
(No.2 experiment sample, AB5 type battery)



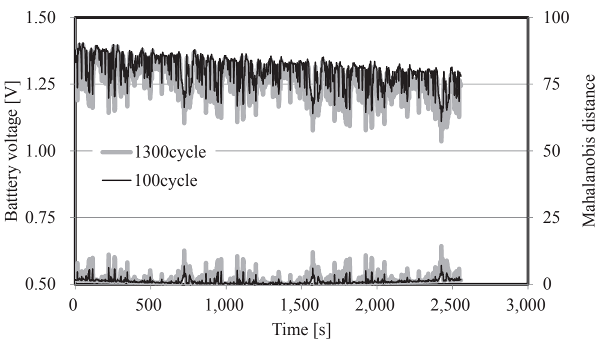
(a) 400 cycle



(b) 700 cycle



(c) 1000 cycle



(d) 1300 cycle

Fig. 7 Battery voltage and Mahalanobis distance (No.3 experiment sample, AB5 type battery)

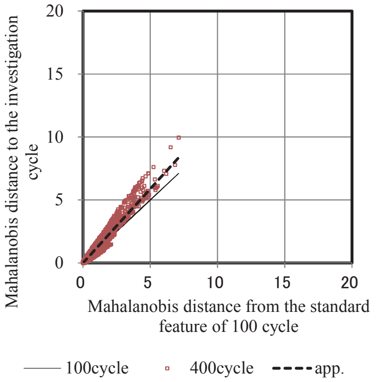
4. Experimental results interpretation

4.1 *Statistical analysis application (SL type battery)*

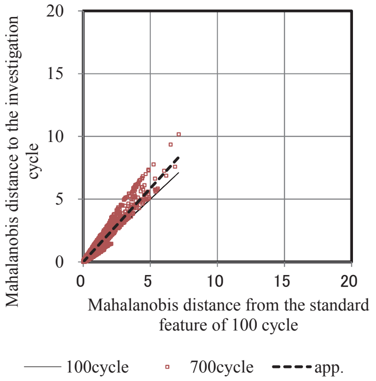
Figures 8 to 10 shows the Mahalanobis distance distribution of the super lattice alloy type experimental battery shown in Figs. 2 to 4 respectively. In Figs. 8 to 10, the center line which the Mahalanobis distance from the standard feature group of the battery terminal voltage of the 100th cycle mode experience to the verification group regressed on itself. The distribution plot points show the Mahalanobis distance from the standard feature group to the verification group of cycle mode voltage. The Mahalanobis distance distribution of the verification group of the battery terminal voltage of cycle mode experience shows much distance from the standard feature group. It is indeed that the actual battery deterioration is in progress with the cycle mode experience which can verify the Mahalanobis distance distribution of the battery terminal voltage information. The Mahalanobis distance distribution of the battery terminal voltage information indicates that the super lattice alloy type batteries change each other in progress of the cycle mode experience although the experimental batteries are like the same terminal voltage transition on the initial stage. In Fig. 10, the drastically change of the Mahalanobis distance distribution can be recognized.

4.2 *Statistical analysis application (AB5 type battery)*

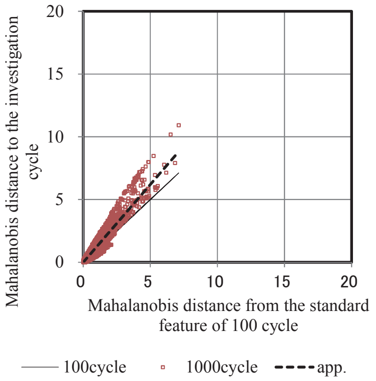
Figures 11 to 13 shows the Mahalanobis distance distribution of the AB5 alloy type experimental battery shown in Figs. 5 to 7 respectively. In Figs. 11 to 13, the center line which the Mahalanobis distance from the standard feature group of the battery terminal voltage of the 100th cycle mode experience to the verification group regressed on itself. The distribution plot points show the Mahalanobis distance from the standard feature group to the verification group of cycle mode voltage. The Mahalanobis distance distribution of the verification group of the battery terminal voltage of cycle mode experience increases the distance in progress of the experience cycles from the standard feature group. It is indeed that the actual battery deterioration is in progress with the cycle mode experience which can verify the Mahalanobis distance distribution of the battery terminal voltage information. The Mahalanobis distance distribution of the battery terminal voltage information indicates that the AB5 alloy type batteries have the same relations to change each other in progress of the cycle mode experience, which coincides with the experimental batteries are like the same terminal voltage transition on the initial stage battery terminal voltage of the 100th cycle mode experience. The AB5 has the honest characteristic of the experiment cycles.



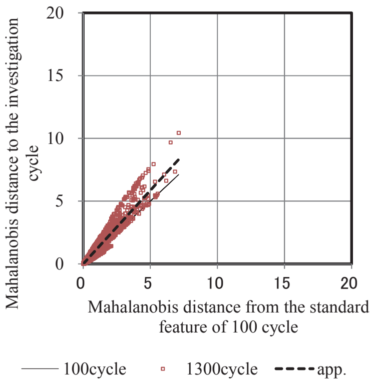
(a) 400 cycle



(b) 700 cycle

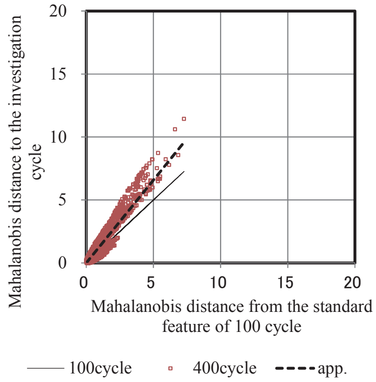


(c) 1000 cycle

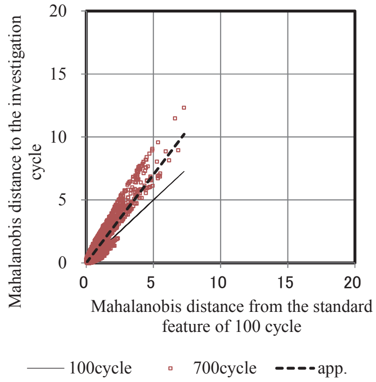


(d) 1300 cycle

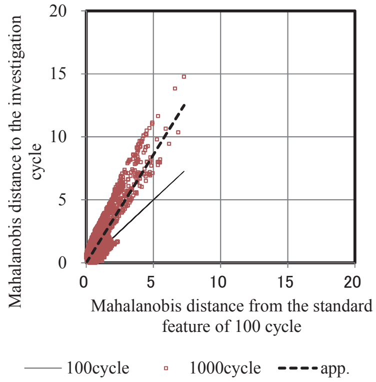
Fig. 8 Mahalanobis distance distribution from the standard feature of 100th cycle voltage, (No.1 SL type battery)



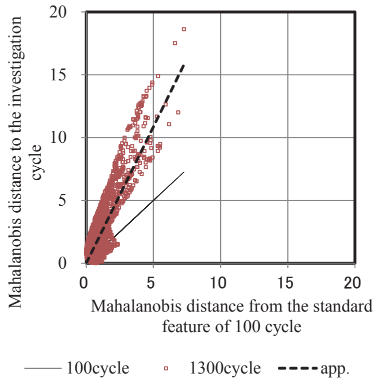
(a) 400 cycle



(b) 700 cycle

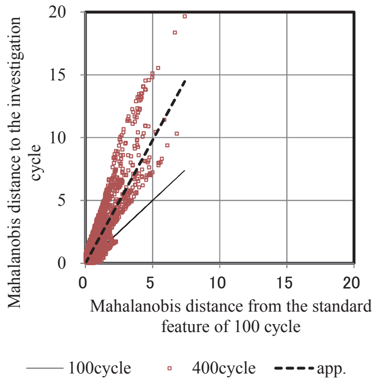


(c) 1000 cycle

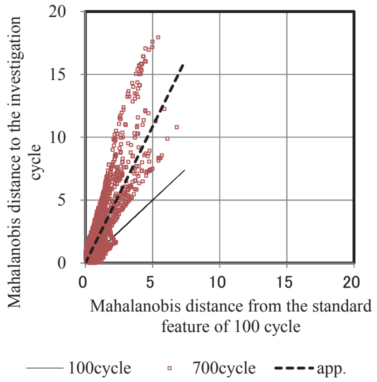


(d) 1300 cycle

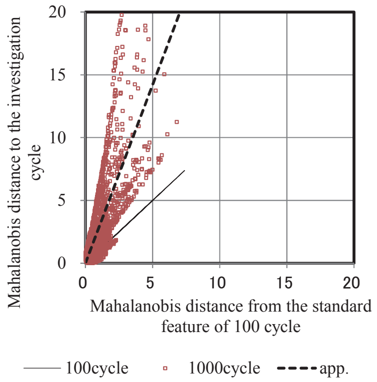
Fig. 9 Mahalanobis distance distribution from the standard feature of 100th cycle voltage, (No.2 SL type battery)



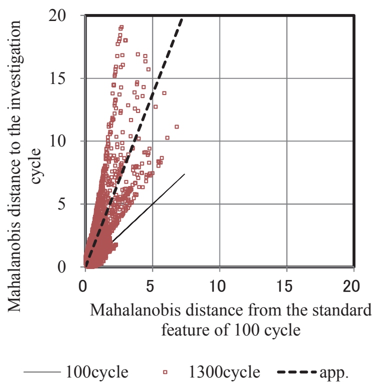
(a) 400 cycle



(b) 700 cycle

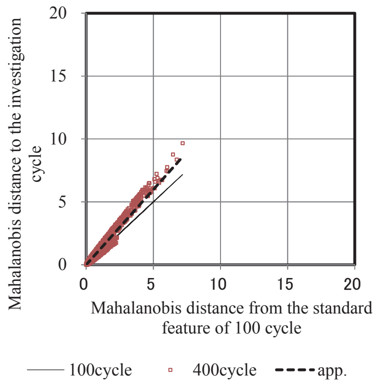


(c) 1000 cycle

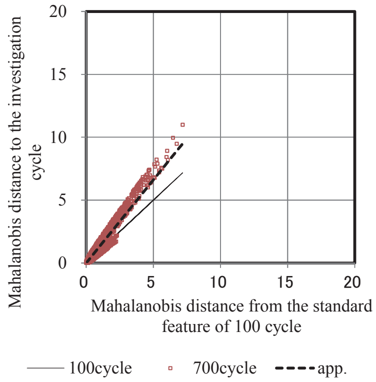


(d) 1300 cycle

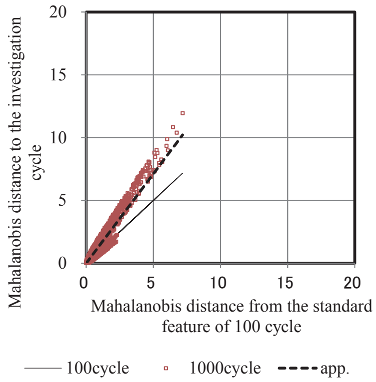
Fig. 10 Mahalanobis distance distribution from the standard feature of 100th cycle voltage, (No.3 SL type battery)



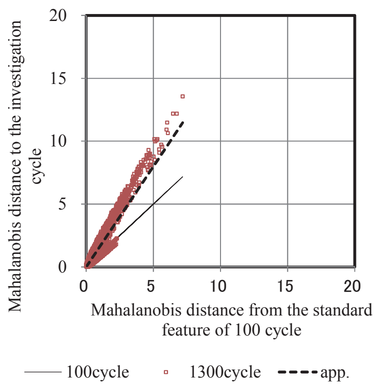
(a) 400 cycle



(b) 700 cycle

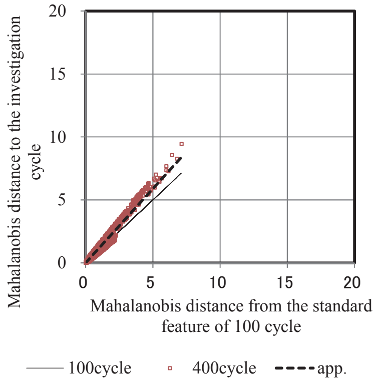


(c) 1000 cycle

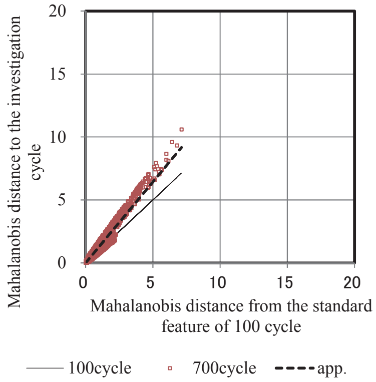


(d) 1300 cycle

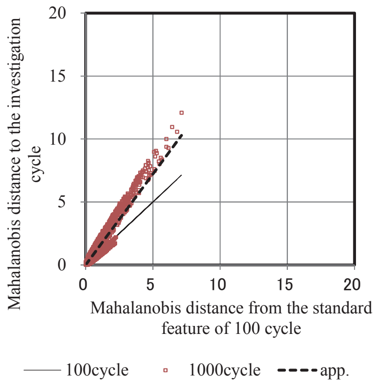
Fig. 11 Mahalanobis distance distribution from the standard feature of 100th cycle voltage, (No.1 AB5 type battery)



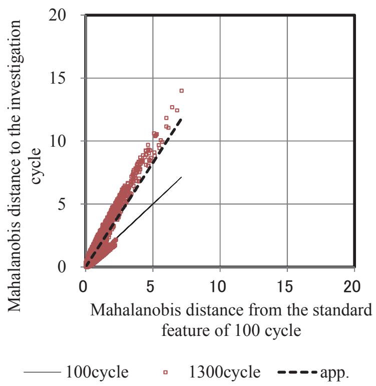
(a) 400 cycle



(b) 700 cycle

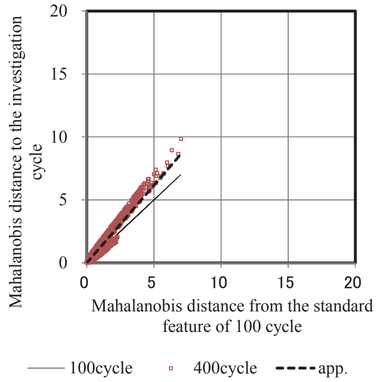


(c) 1000 cycle

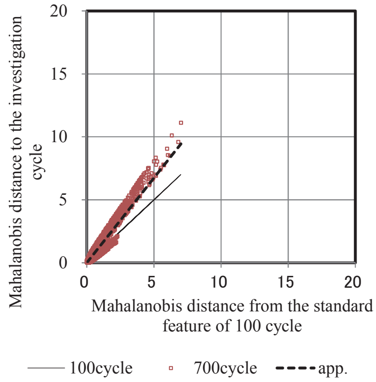


(d) 1300 cycle

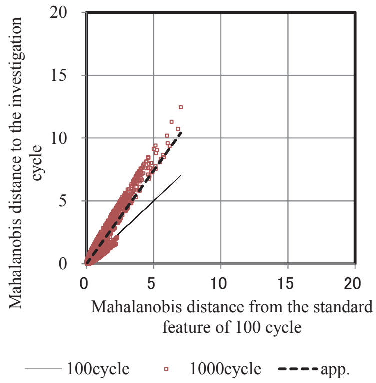
Fig. 12 Mahalanobis distance distribution from the standard feature of 100th cycle voltage, (No.2 AB5 type battery)



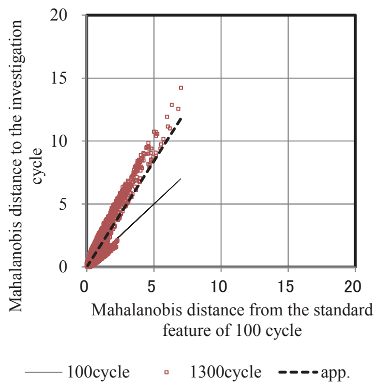
(a) 400 cycle



(b) 700 cycle



(c) 1000 cycle

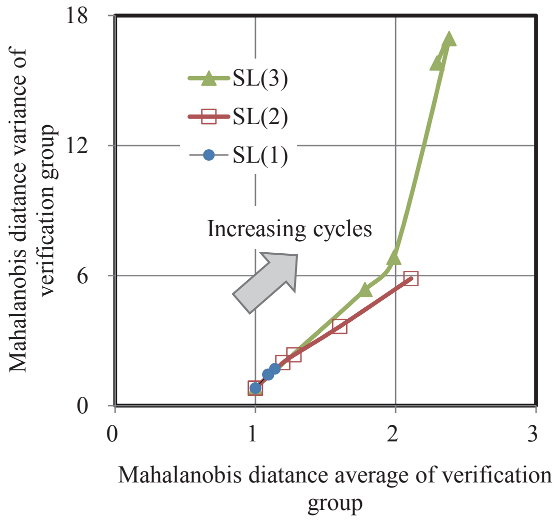


(d) 1300 cycle

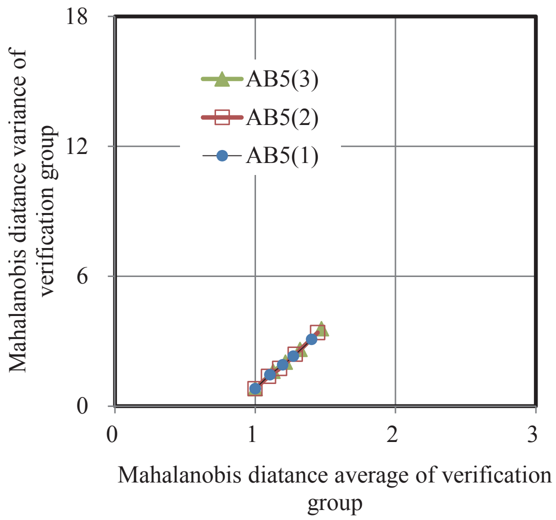
Fig. 13 Mahalanobis distance distribution from the standard feature of 100th cycle voltage, (No.3 AB5 type battery)

5. Discussion

Figure 14 shows the Mahalanobis distance distribution of the verification groups. The horizontal axis is an average of the Mahalanobis distance distribution of the verification group and the vertical axis is a variance of the Mahalanobis distance distribution of the verification group. Each plot points are the experiment cycle of 100, 400, 700, 1000 and 1300 cycle respectively. The plot points are shown from the left bottom in the experiment cycle order of seniority.



(a) SL type battery



(b) AB5 type battery

Fig. 14 Mahalanobis distance distribution from the standard feature of 100th cycle voltage, (No.3 experiment sample, AB5 type battery)

Fig. 14 (a) shows three sample relations of the super lattice alloy type experimental battery. It can be recognized that the each sample battery characteristics are different from the relations between the Mahalanobis distance average of the group distribution and the Mahalanobis distance variance of the group distribution in progress of the experiment cycles. Especially, the No.3 experiment sample battery SL (3) which is drastically change the relations from the 1000 cycle on. Fig. 14 (b) shows three sample relations of the AB5 alloy type experimental battery. It can be recognized that the each sample battery characteristics are the same relations between the Mahalanobis distance average of the group distribution and the Mahalanobis distance variance of the group distribution in progress of the experiment cycles. The Mahalanobis distance average of the group distribution and the Mahalanobis distance variance of the group distribution can be recognized that the AB5 alloy type batteries have an honest characteristic in progress of the experiment cycles.

6. Conclusion

This study verified with two types of different alloy structure of Ni-MH battery and acquired following knowledge.

(1) The drop range of the battery terminal voltage grows larger along with the experiment cycle increase which can be recognized of the Mahalanobis distance.

(2) The actual battery deterioration is in progress with the cycle mode experience which can verify the Mahalanobis distance distribution of the battery terminal voltage information.

(3) The Mahalanobis distance average of the group distribution and the Mahalanobis distance variance of the group distribution can be recognized that the super lattice alloy type battery characteristics are drastically different in three samples, although the AB5 alloy type battery characteristics are well matched in three samples in progress of the experiment cycles.

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References

1) Kameyama, H.; *Study on Heat Generation Behavior at Small Lithium-ion Secondary Battery*, JSME No.02-7 The 8th Symposium on Prime Mover and Energy Engineering, Tokyo, (2002), pp.387-392 (in Japanese).

2) Mueller, J. M.; *Characterization of Direct Methanol Fuel Cells by AC Impedance Spectroscopy*, Journal of Power Sources 75, (1998), pp.139-143.

3) Itagaki, M.; *Electrochemical Impedance Method*, Maruzen, Tokyo, (2011), pp.61-62 (in Japanese).

4) Iwasaki, A., Todoroki, A., Shimamura, Y., Kobayashi, H.: Damage Identification by Discriminant Analysis Using Mahalanobis Distance (in Japanese), Transactions of the Japan Society of Mechanical Engineers (2001), Series A, Vol.67, No.659, pp.1242-1247

5) Nakatsugawa, M., Ohuchi, A.: A study on Determination of the Threshold in MTS Algorithm (in Japanese), Journal of Institute of Electronics Information and Communication Engineers (2001), Vol.J84-A, No.4, p.520

6) Takagi, Y., Inujima, H., Matsumoto, M.: Evaluation for Life-expectancy Presumption Technique of Aged Switchboards Based on MTS Method (in Japanese), The transactions of the Institute of Electrical Engineers of Japan. D, A publication of Industry Applications Society, IEEJ transactions on industry applications (2006), Vol.126, No.6, p.805

7) Taguchi, G.: Mathematics for Quality Engineering, First version (1999), pp.145-152, Japanese Standards Association

8) Miyakawa, M.: Technologies for Getting Quality, First version (2000), pp.220-225, Union of Japanese Scientists and Engineers Press

9) Sakamoto, T., AC Impedance Spectroscopy Analysis (Applied for Electrical Prime Mover On-board Energy Storage), International Conference on Engineering, Applied Sciences, and Technology (ICEAST 2013), Bangkok Thailand, pp.132-135.

10) Sakamoto, T., Battery Cell Temperature Transition of Hybrid Electric Vehicle Driving from Bangkok to Ayutthaya –(2012), Proceedings of 2012 Society of Automotive Engineers of Japan (JSAE) Annual Congress (Spring), pp.1-4

11) Sakamoto, T., Electric Load Analysis of Hybrid Electric Vehicle at Commuting Monitor(2010), Proceedings of 2010 Society of Automotive Engineers of Japan (JSAE) Annual Congress (Spring), pp.17-21.

12) Sakamoto, T., Battery SOC State of a Hybrid Electric Vehicle, Journal of Mechanical Systems for Transportation and Logistics, Vol.2, No.2 (2009), pp.121-132.