Development of Li-ion Battery Bulk Force and Expansion Displacement Test-bench

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Abstract. In order to test the bulk force and expansion displacement of lithium-ion batteries, it is planned to develop a corresponding test-bench, which is mainly composed of a measurement-control system and a mechanical system. To improve the accuracy of the test data, the coupled thermal-structure simulation of the test system in the mechanical system of the test-bench is carried out to select an optimal mechanical structure of the test system. At the same time, for safe and convenient testing, a monitoring-testing system software was developed to ensure the reliability and safety of data collection. Finally, through the test-bench, the battery expansion displacement-SOC curve and the battery bulk force-SOC curve under different discharge rates were tested, providing a basis for the development of a battery management system coupling temperature-current-voltage-displacement-force.

Keywords: Battery Management System, Bulk force, Expansion Displacement, Finite Element Analysis

1. Introduction

Now, all over the world, Lithium-ion batteries are widely used in daily life. However, there are still many challenges in the use of lithium-ion batteries, such as thermal runaway, performance degradation at low temperatures, inconsistency, incorrect state of charge prediction, life decay and so on.

Therefore, in order to find more accurate and efficient ways to solve the above problems, in recent years, more and more researchers began to study the relationship between the mechanical response and the performance of lithium-ion battery. Sergiy et al. studied the deformation and failure modes of lithium battery separators under biaxial tension and established a finite element model to predict this response [1]. Fu et al. established a stress model for a soft-pack lithium battery that considers the stress caused by the ion concentration in the electrode particles on the basis of electrochemical and thermal models [2]. Besides, Yong et al. and Peabody studied the influence of lithium-ion external compression load on the cycle life of lithium-ion batteries, and the results showed that applying a proper pre-compression load can effectively improve the cycle life of lithium-ion batteries [3-4].

In conclusion, the existing research has fully confirmed that there is a strong correlation between the performance of lithium-ion battery and its mechanical response. Therefore, in this paper, in order to measure the relevant mechanical response more accurately during the process of charging and
discharging, and thus more accurately and comprehensively study the relationship between the performance of li-ion batteries and the mechanical response of li-ion batteries, a test-bench which can add preload and can test the expansion displacement, strain, temperature and bulk force of the li-ion battery has been developed.

2. Design of Mechanical System and Measurement-control System of Test-bench

2.1. Principle of the Test-bench

The purpose of this test-bench is to accurately collect the data of expansion force, displacement, strain and temperature changes caused by thermal expansion, lithium-ion insertion and removal during the charging and discharging process of lithium-ion battery, so as to provide reference for the subsequent performance research of li-ion battery.

The test-bench mainly is composed of mechanical and measurement-control system. Where the mechanical system plays a role in fixing the test battery, transferring movement displacement and heat dissipation. In addition, the measurement-control system mainly includes charge-discharge control system, environment control system and monitoring-testing system. The function of charge-discharge control system is to charge and discharge lithium-ion battery, including battery charging and discharging equipment; the function of environmental control system is to ensure the environmental stability in the process of battery charging and discharging, including thermal chamber; The function of the monitoring-testing system is to collect the expansion displacement, bulk force, strain, temperature, voltage and current of the battery during the test, and monitor the temperature of the battery surface to prevent the battery from overheating. The equipment mainly includes various sensors, Ni analog input modules, a CompactDAQ and a computer. Test virtual layout diagram is shown in Fig. 1.

![Figure 1. Test virtual layout diagram](image1)

**Figure 1. Test virtual layout diagram**

1-fixed plate of displacement sensor; 2-fixed plate of upper spacer; 3-upper and lower fixed spacer of battery; 4-Battery; 5-supporting shaft; 6-fixed cross plate of lower spacer; 7-connecting plate of slide block; 8-slider block; 9-Slideway; 10-fixed plate of weighing sensor; 11-bolts and lock nuts

![Figure 2. Structure of the test-bench](image2)

**Figure 2. Structure of the test-bench**
2.2. Mechanical Structure Design of Test-bench

The test-bench should be designed to realize the concurrent test of any number of batteries in the range of 1-4 under constraint conditions and free conditions. Under the constraint conditions, the test-bench can apply certain preload to different number of batteries together, and then test the bulk force, temperature, and strain data of all concurrent testing batteries under various working conditions. Under free conditions, it should be able to test the expansion displacement of lithium-ion batteries under different charging and discharging conditions. In order to carry out the above two kinds of tests on the same test-bench and accurately measure the relevant mechanical response of lithium-ion battery in the above test process, the mechanical structure of the test-bench is designed as shown in the Fig. 2.

In the mechanical structure of the test-bench, in order to ensure the stability and effective positioning of the battery in the process of charging and discharging, a groove matched with the spacer is left on the fixed cross plate of lower spacer 6 and the fixed plate of upper spacer 2. The spacer in the test-bench mainly plays the role of simulating the constrained conditions of lithium-ion battery in the battery pack and transferring the expansion force and displacement of lithium-ion battery in the process of charging and discharging to the sensor. At the same time, it also plays the role of heat dissipation, insulation and easy to measure the surface temperature and strain of the battery. In order to realize the above functions of the spacer, the spacer is made of fiber reinforced nylon material, and two structural schemes are designed, as shown in Fig. 6. The coupled thermal-structural analysis should be carried on the actual test system composed of above two kinds of spacers and lithium-ion battery, so as to determine an optimal spacer structure for the actual test system.

2.3. Software Design of Monitoring-testing System for Test-bench

The measurement-control system of the test-bench mainly includes three parts: charge-discharge control system, environment control system and monitoring-testing system. The charge-discharge control of lithium-ion battery is completed by the charge-discharge equipment and PC. The ambient temperature of lithium-ion battery during charging and discharging is controlled by the thermal chamber. The functions of acquiring, storing, displaying, and monitoring testing data are mainly completed by the software of the monitoring-testing system written by LabVIEW and related hardware.

The main test data acquired by the monitoring-testing system of the test-bench are the expansion displacement, strain, bulk force and temperature of the battery, and the change of the battery temperature is monitored. In addition, the current and voltage signal collection is completed by the charge-discharge equipment and the PC. Based on the previous analysis and the functions of the monitoring-testing system, the hardware structure of the monitoring-testing system of the test-bench as shown in Figure 3.

![Figure 3. Hardware structure of the test-bench monitoring-testing system](image-url)
The software of monitoring-testing system mainly includes login interface module and start test interface module. The design of the start test interface adopts the message queue design mode, in which there are four running threads, which are event processing loop, UI message processing loop, data acquisition and storage and data display thread, as show in Fig. 4 and Fig 5. The communication between them mainly depends on registered dynamic user events, message queues and notifiers. The data acquisition and storage thread are used to collect the temperature, strain, displacement, and force data and store them in the corresponding database. At the same time, the collected data is broadcast through the notifier, waiting for the data display thread to receive. When the collected temperature data exceeds the set value, the temperature monitoring module will send a warning message to remind the test personnel.

3. Finite Element Simulation Verification of the Test-bench
The measured bulk force and displacement will be inaccurate or even unable to be measured, if the
stiffness of the test-bench is insufficient, because the small expansion displacement during the process of lithium battery charging and discharging. Therefore, the finite element simulation is needed to ensure that the developed test-bench has high stiffness. The charge and discharge process of lithium battery is a complex coupled chemical-thermal-mechanical-electrical process, which is difficult to accurately simulate the mechanical response of the battery. Because the development of the test-bench is mainly concerned with the stiffness and strength of the test-bench caused by the expansion of the lithium battery during the charging and discharging process, the complex thermal-mechanical-electrical coupling process between the lithium battery and the test-bench can be simplified as a coupled thermal-structure process between the lithium battery and two spacers.

It can be seen from Fig. 6 that the shape variable of first scheme is larger than that of second scheme, and the place with the largest deformation is the bulge part of the contact between the battery and the spacer. It absorbs the expansion displacement of lithium battery, which makes the sensor unable to measure the expansion displacement. The deformation distribution of scheme 2 is uniform and small, so the spacer of scheme 2 is selected finally.

![Scheme 1 cloud deformation](image1.png) ![Scheme 2 cloud deformation](image2.png)

(a) Scheme 1 cloud deformation  (b) Scheme 2 cloud deformation

**Figure 6.** Finite element simulation results of two kinds of spacers

4. **Charge-discharge Test and Test Result Analysis**

4.1. **Expansion Displacement Signal**

In order to verify the reliability of the test-bench, the following li-ion battery charging and discharging tests are designed: the li-ion battery is charged to 4.2 V at a constant current of 1 C, and then charged at a constant voltage until the current drops to 0.02 C; Let it stand for 30 min; Then discharge at different discharge rates. Finally, the expansion displacement-SOC curves can be get at different discharge rates, as shown in Fig. 7.

![Expansion displacement curve](image3.png)

**Figure 7.** Expansion displacement curve

By analysing the test data, it can be concluded that the expansion displacement curves under different discharge rates in Fig. 7 have similar regular changes. It can be also seen that the
repeatibility of the test-bench is good, and the magnitude of the expansion displacement measured by the test-bench is close to the existing literature [5-9]. Therefore, the expansion displacement data measured by the device designed in this paper is reliable.

4.2. Bulk Force Signal
Because the overall structure of the test-bench is more complex, and from the previous simulation results, the test-bench will deform in the process of experiment, and because the spacer material is polymer material, which has a certain damping, the force measured by the load cell may be smaller than the real expansion force in the actual measurement process, so it is necessary to correct the force signal. According to the finite element simulation results, the pressure difference curves on the contact surface between the li-ion battery and the front spacer can be obtained, as shown in Fig. 8. Therefore, the following formula can be used to correct the force signal:

\[ F_1 = 164.9736x^2 + 32.8716x - 0.3286 \]  \hspace{1cm} (1)

![Figure 8. Pressure difference curve](image)

![Figure 9. Rebound curve](image)

In formula (1), \( x \) is the expansion of li-ion battery. At the same time, in order to correspond the force and displacement data one by one, the rebound resistance of the displacement sensor itself should be considered. The rebound curve measured by experiment is shown in Fig. 9. According to Fig. 9, the elastic force-displacement formula (2) can be got and its correlation coefficient is 0.9915. Although the values of the bulk force error and the rebound resistance are relatively small during the entire discharge process, the bulk force becomes smaller due to the discharge process and the value of the load cell at the end of the discharge is also small, as shown in Fig. 9, so these errors need to be considered. Finally, the corrected force signal is in formula (3), where \( F_0 \) is the sensor reading; \( F \) is the corrected bulk force.

\[ F_2 = 0.0806x + 0.6061 \]  \hspace{1cm} (2)

\[ F = F_0 + F_1 - F_2 \]  \hspace{1cm} (3)
4.3. Relationship between Bulk Force and Expansion Displacement

Finally, the expansion force-expansion displacement curve of 1.5C discharge ratio can be obtained through Fig. 7 and Fig. 10, as shown in Fig. 11. The curve can provide basic data for the establishment of Li-ion battery multi physical coupled electrical-thermal-mechanical model and lay the foundation for the establishment of battery management system coupling electrical-thermal-mechanical signals.

5. Conclusion

In this paper, a battery expansion force and displacement test bench and monitoring-testing software are designed and developed. Besides, finite element simulation is also carried out to improve the accuracy of the test data. In addition, aiming at the loss of force transmission in the test process, the error and resilience of the expansion force data are corrected. Finally, based on the developed test-bench, the expansion displacement-SOC curve and the bulk force-SOC curve are obtained from the measured test data. At the same time, the bulk force-expansion displacement curve is also obtained by taking SOC as an intermediate variable, which provides basic data for the establishment of battery management system coupling electric-thermal-force signals.

Acknowledgments

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References

[1] Sergiy K, Abhishek K, Yanli W, et al, Strain distribution and failure mode of polymer separators for Li-ion batteries under biaxial loading, Journal of Power Sources, 378 (2018) 139-145.
[2] Fu R, Xiao M, Modeling, validation and analysis of mechanical stress generation and dimension changes of a pouch type high power Li-ion battery, Journal of power sources, 224 (2013) 211-224.
[3] Yong H C, Hae K L, Development of standardized battery pack for next generation PHEVs in considering the effect of external pressure on lithium-ion pouch cells, SAE International
[4] Peabody, C. and C.B. Arnold, The role of mechanically induced separator creep in lithium-ion battery capacity fade, Journal of Power Sources. 196 (2011) 847-853.

[5] Cannarella J, Arnold C B . Stress evolution and capacity fade in constrained lithium-ion pouch cells, Journal of Power Sources. 245 (2014) 745-751.

[6] Choi Y H, Lim H K, Seo J, Development of Standardized Battery Pack for Next-Generation PHEVs in Considering the Effect of External Pressure on Lithium-Ion Pouch Cells, SAE International Journal of Alternative Powertrains. 7 (2018) 195-205.

[7] Wünsch, Martin, Kaufman, Jörg, Sauer D U, Investigation of the influence of different bracing of automotive pouch cells on cyclic lifetime and impedance spectra, Journal of Energy Storage. 21 (2019) 149-155.

[8] Barai A, Tangirala R, Uddin K, The effect of external compressive loads on the cycle lifetime of lithium-ion pouch cells, Journal of Energy Storage. 13 (2017) 211-219.

[9] Mussa A S, Klett M, Göran Lindbergh, Effects of external pressure on the performance and ageing of single-layer lithium-ion pouch cells, Journal of Power Sources. 385 (2018) 18-26.