Characteristics Numerical Research on Power Battery Impact Strength of New Energy Vehicle

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Based on the crash test of new energy vehicles, the mechanical response data of power batteries during the collision process were collected, and the average impact strength curve of power batteries of typical new energy vehicles in China was obtained. The average impact strength curve was mathematically processed to obtain the impact strength characteristic value and tolerance by using the equivalent trapezoidal wave and the least square method, thereby determining the test conditions of the dynamic strength of the domestic new energy vehicle power battery. The differences are analyzed by comparing with ISO 12405-3 test conditions, which provides an important reference for the revision of power battery test standards in the future.

Keywords: Power battery; mechanical shock strength; least square method; equivalent trapezoidal wave.

1. Introduction

Under the double crisis of energy and environment, it is inevitable that the automobile industry will improve the energy efficiency of automobiles and reduce the discharge of pollutants [Liyang (2009)]. The requirements for energy conservation and environmental protection are constantly improving. Therefore, new energy vehicles, especially A0, A-class vehicles are increasingly favored by the market in China.

The impact safety of power batteries in new energy vehicles should not be ignored. The impact strength is directly related to the injury of occupants. The greater the intensity, the greater the damage. ISO 124505-3 for batteries test

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of new energy vehicles was established abroad,^a and the Crash Safety Working Group (CSWG) of the United States Council for Automotive Research (USCAR) researched the idealized vehicle crash test pulses of the batteries under American crash standards [Zhiping and Linying (2008)]. However, at present, there is no standard with consideration of national conditions for the dynamic strength of power batteries for new energy vehicles in China. The accumulation of test data supporting the development of standards has not yet been carried out. With the rapid development of new energy vehicles, the follow-up of relevant safety standards is imminent.

According to the vehicle crash test, the mechanical response data of the power battery for the A0, A-class new energy vehicles during the collision test is obtained in this paper. The average curve of the dynamic impact strength of the power battery is obtained statistically. The impact strength characteristic value and tolerance are obtained by equivalent trapezoidal wave and least squares method. The dynamic strength test conditions of the new energy vehicle power battery complying with China national conditions are determined. It provides an important reference for the revision of future power battery pack test standards by benchmarking the ISO 124505-3 test conditions and performing parameter difference analysis.

2. Power Battery Collision Strength Data Acquisition

The research object is A0, A-class new energy vehicle (referred to as A0, A-class car in the text). The actual vehicle crash test mode is 50 KPH front rigid barrier collision (GB11551-2015) and 50 KPH side deformable barrier collision (GB20071-2006).

An acceleration sensor is mounted at the body floor and the geometric center of the battery surface corresponding to the center position of the power battery to measure the collision strength of the power battery. The acceleration sensor damping coefficient is 0.05. Lateral sensitivity is less than 1%. Nonlinearity and

Fig. 1. Power battery sensor installation location.

^aISO 12405-3-2014. Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems — Part 3: Safety performance requirements.

hysteresis (reading and full scale) are controlled within $\pm 1\%$. In the data processing, the Butterworth low-pass filter is used for filtering. The filtering frequency level is CFC60.

2.1. Frontal collision data analysis

Thirteen representative vehicle model test data are obtained for A0 class vehicles. Nine representative vehicle model data are obtained for A class vehicles. Figures 2 and 3 show the collision response waveforms of A0 class and A class vehicles respectively. Figure 4 is a front impact average impact waveform after statistical processing.

Fig. 2. Distribution of frontal crash acceleration waveforms of A0 class vehicles.

Fig. 3. Distribution of frontal crash acceleration waveforms of A class vehicles.

Fig. 4. Comparison of the average impact waveform of A0 class and A class vehicles.

Fig. 5. Comparison of front end structure of A0 class vehicle (left) and A class vehicle (right).

The frontal impact waveforms of A0 class and A class vehicles are arithmetic averaged, and the average impact waveforms of frontal impacts are obtained. The average waveform pulse width is 90 ms and the peak value is around 32 g for the A0 class vehicle. For the A class vehicle, the average waveform pulse width is 110 ms and the peak value is around 30 g.

It can be found by comparing with the front end structure of the A0 and the A-class body (Fig. 5). Due to the size constraints of the model, the front end space of the A0 class vehicle is limited and the energy absorption structure is simple. The initial acceleration of the collision is significantly greater than that of the A-class vehicle. Also due to the size of the vehicle, the peak acceleration of the A0 class vehicle is generated earlier than the A class vehicle. The A-class vehicle usually has the longitudinal beam, the sub-frame and other components of the traditional fuel vehicle, which can effectively absorb energy. Therefore, the initial acceleration of the collision is small, the acceleration curve is relatively flat and the peak acceleration occurs relatively late.

Therefore, there is a difference in the impact response characteristics of the battery pack corresponding to the A0 and A-class vehicles. For different models, the battery pack should be evaluated with different impact strength.

2.2. Side impact data analysis

Nine representative vehicle model data are obtained for the A0 class vehicle. Eight representative vehicle model data are obtained for the A-class vehicle. Figures 6 and 7 show the collision response waveforms of A0 class and A class vehicles respectively. Figure 8 is a side impact average impact waveform after statistical processing.

The side impact waveforms of A0 class and A class vehicles are arithmetic averaged, and the average impact waveforms of side impacts are obtained. The average waveform pulse width is 70 ms and the peak value is around 24 g for the A0 class car. However, for the A-class vehicle, the average waveform pulse width is 80 ms and the peak value is around 12 g.

Fig. 6. Acceleration wave pattern distribution of side collision of A0 class vehicles.

Fig. 7. Acceleration wave pattern distribution of side collision of A-class vehicles.

Fig. 8. Comparison of the side average impact waveform of A0 class and A-class vehicles.

It can be found by comparing the average impact waveform on the side. Because of the small mass, the A0-class vehicle is subjected to a large acceleration load during the collision process. The acceleration rises quickly and the peak is sharp. This means that the collision process is relatively short. The acceleration drops rapidly after the vehicle is pushed open. For the A-class vehicle, due to the relatively large mass and side energy absorption space, the acceleration peak is gentle, the peak is almost half of the A0 vehicle, and the frequency response lasts longer.

Therefore, for the side impact, the impact characteristics of the A0-class vehicle and the A-class vehicle power battery are also different. The battery pack should be also evaluated with different impact strength.

3. Mathematical Processing of Power Battery Impact Strength

The average impact strength of the power battery is mathematically processed by using the least squares method and trapezoidal wave to obtain the corresponding equivalent waveform. The dynamic intensity characteristic value is determined. Specifically, the test waveform channel is determined according to the average impact waveform. This channel should be centered on the average waveform and matched with the upper and lower tolerances to determine the dynamic impact test conditions.

3.1. Equivalent trapezoidal wave calculation method

The correspondence between the trapezoidal waveform acceleration curve, the velocity curve and the displacement curve is shown in Fig. 9 [Huang (2002)]. Here a represents the acceleration curve, v represents the velocity curve; d represents the displacement curve; T_1 is an inflection point of the acceleration trapezoidal curve; e is the slope corresponding to this segment; A is the maximum value of the acceleration waveform; T_m is the second inflection point and also the maximum moment of the displacement curve; T_f is the moment when the acceleration waveform is reset to zero; v_0 is the speed at time 0; v_1 is the speed at time T_1 ; d_1 is the displacement at time T_1 ; and C is the maximum value of the displacement curve.

Deformation phase 0 ~ T1 phase:

$$\begin{cases} a = et \frac{A}{T_1} t \\ v = v_0 + \int_0^t a dt = v_0 + \frac{e}{2} t^2 \\ d = v_0 t + \frac{e}{6} t^3. \end{cases} \quad (1)$$

Fig. 9. Collision acceleration ladder diagram.

The boundary condition of $t = T_1$ is $a = eT_1$

$$\begin{cases} v_1 = v_0 + \frac{e}{2}T_1^2 = v_0 + \frac{AT_1}{2} \\ d_1 = v_0T_1 + \frac{e}{6}T_1^3 = v_0T_1 + \frac{AT_1^2}{6}. \end{cases} \quad (2)$$

Continuous deceleration phase: $T_1 \sim T_M$

$$\begin{cases} v = v_1 + \int_{T_1}^t a dt = v_0 + \frac{AT_1}{2} + A(t - T_1) \\ d = d_1 + \int_{T_1}^t v dt = v_0T_1 + \frac{AT_1^2}{6} + \int_{T_1}^t \left(v_0 + \frac{AT_1}{2} + A(t - T_1) \right) dt \\ \quad = \frac{At^2}{2} + \left(v_0 - \frac{AT_1}{2} \right) t + \frac{AT_1^2}{6}. \end{cases} \quad (3)$$

When $T = T_m$, the boundary condition is:

$$\begin{cases} v = v_m = 0 \\ 0 = v_0 + \frac{AT_1}{2} + A(T_m - T_1) \\ T_1 = \frac{2}{A}(v_0 + AT_m), \end{cases} \quad (4)$$

$$\begin{cases} d = C \\ C = \frac{AT_m^2}{2} + \left(v_0 - \frac{AT_1}{2} \right) T_m + \frac{AT_1^2}{6}. \end{cases} \quad (5)$$

Bring T_1 to C and get:

$$T_m^2 A^2 + 2(4v_0T_m - 3C)A + 4v_0^2 = 0. \quad (6)$$

From the equation, it can be found that

$$A = \frac{-(4v_0T_m - 3C) + \sqrt{(4v_0T_m - 3C)^2 - 4v_0^2T_m^2}}{T_m^2}. \quad (7)$$

Both the velocity and displacement curve are obtained by integrating the experimental acceleration waveform. The integral equation and the calculation equation are established according to the above relationship in MATLAB Simulink.

The equivalent trapezoidal wave calculation method (Fig. 9) is used to process the frontal collision average waveform of the A0 and A-class vehicles (Fig. 4), and the corresponding equivalent trapezoidal wave can be obtained.

3.2. Least squares method

For the side impact test, since there is no rebound time, the T_m time in Fig. 9 cannot be determined. So the equivalent trapezoidal wave calculation method is not

Fig. 10. Least squares diagram.

applicable. Therefore, the least square method is used to fit the average waveform of the side collision to form a trapezoidal wave. The specific method is as follows: According to the principle of least squares method, the sum of the squares of the difference between the measured value y_i and the calculated value y is the criterion of optimization. That $\sum(y_i - y)^2$ is the minimum [Zhiping and Linying (2008)]. The correlation difference equation can be established according to the trapezoidal wave curve and the original curve of Fig. 10.

$$\varphi_1 = \sum(y_i - y)^2 = \sum \left(y_i - \frac{A}{T_N} T_i \right)^2 \quad T_i \leq T_N, \quad (8)$$

$$\varphi_2 = \sum(y_i - y)^2 = \sum (y_i - A)^2 \quad T_N < T_i \leq T_M, \quad (9)$$

$$\varphi_3 = \sum(y_i - y)^2 = \sum \left(y_i - \frac{T_f - T_i}{T_f - T_M} A \right)^2 \quad T_i > T_M. \quad (10)$$

Here, A , T_M and T_N can be calculated by MATLAB. Further, a trapezoidal curve is obtained. The corresponding equivalent trapezoidal wave can be obtained by using the least squares method to process the side impact average waveform of the A0 class and A class vehicles.

3.3. Calculating result of equivalent trapezoidal wave

The A0 class and A class vehicles are equivalently calculated on the front and side average impact waveforms to obtain four equivalent trapezoidal waves by using the equivalent trapezoidal wave construction method and the least squares method (shown in Fig. 11). Name the four vertices of the trapezoidal wave in chronological order by 1–4 (Table 1).

The waveform space tolerance range is need to be determined after determining the equivalent trapezoidal wave. In this paper, only for the purpose of signal comparison, the width of the peak part channel in ECE R100 is referenced in the channel width setting. The trapezoidal wave is scaled according to a certain ratio^b to obtain the lower and upper limits of the front and side impact test waveforms of

^bUNECE R100 — Uniform provision concerning the approval of battery electric vehicles with regard to specific requirements for the construction, functional safety and hydrogen emission.

Fig. 11. Average equivalent trapezoidal impact wave.

Table 1. Equivalent trapezoidal wave parameters (time/ms, acceleration/g).

Name	Front impact				Side impact			
	A0 class		A class		A0 class		A class	
	Time	Acceleration	Time	Acceleration	Time	Acceleration	Time	Acceleration
1	0	0	0	0	0	0	0	0
2	21	24	47	28	22	23	20	12
3	66	24	73	28	38	23	52	12
4	99	0	113	0	70	0	84	0

the A0 class and A class vehicles, as shown in Figs. 12–15. The eight characteristic points corresponding to the lower limit and upper limit of the impact test waveform are named A–H (Fig. 16). The corresponding impact test characteristic values and tolerance intervals are shown in Table 2.

Fig. 12. A0-class vehicle power battery front impact test waveform.

Fig. 13. A-class vehicle power battery front impact test waveform.

Fig. 14. A0-class vehicle power battery side impact test waveform.

Fig. 15. A-class vehicle power battery side impact test waveform.

Fig. 16. Description of each feature point of the impact waveform.

Table 2. Power battery dynamic impact test parameters (time/ms, acceleration/g).

Characteristic points	Front impact				Side impact			
	A0 class		A class		A0 class		A class	
	Time	Acceleration	Time	Acceleration	Time	Acceleration	Time	Acceleration
A	17	0	19	0	10	0	15	0
B	31	20	55	23	25	20	26	8
C	55	20	60	23	32	20	44	8
D	82	0	94	0	60	0	66	0
E	0	17	0	11	0	10	0	8
F	11	28	39	33	19	27	14	15
G	77	28	85	33	44	27	60	15
H	116	0	132	0	81	0	102	0

Therefore, the power battery dynamic strength test parameters based on the Chinese vehicle test data are determined.

4. Dynamic Test Impact Parameter Comparison and Discussion

4.1. Parameter comparison

A series of test methods and requirements for battery packs and systems in ISO 12405-3 “Electric road vehicles — Test specifications for lithium-ion power batteries and systems — Part 3: Safety performance requirements”. The requirements for dynamic strength testing of battery packs in ISO are shown in Figs. 17 and 18. The waveform channel parameters determined above are compared with ISO.

The results of the A0 class vehicle front collision waveform comparison is shown in Fig. 19. It is found that the average equivalent trapezoidal wave of the A0-class vehicle is mostly in the ISO channel range, especially the peak is almost perfectly passing through the center of the ISO channel. The pulse width is shorter than ISO. The slope of the curve, especially at the beginning of the collision, is significantly larger than ISO.

Fig. 17. ISO12405 frontal simulation crash test curve threshold.

Fig. 18. ISO12405 side simulation crash test curve threshold.

Fig. 19. Comparison of frontal impact parameters and ISO parameters of A0 class vehicles.

Fig. 20. Comparison of frontal impact parameters and ISO parameters of A-class vehicles.

Figure 20 shows the comparison results of the A-class vehicle' front impact waveform. It can be seen that the equivalent impact waveforms almost all fall in the ISO channel, the time history is very close, and the peak value is much higher than the ISO average waveform.

The results of the side collision waveform comparison are shown in Figs. 21 and 22. It can be seen that the A0 and A-class vehicles have significant differences with the ISO on the side impact parameters.

Table 3 is a summary comparison table of impact parameters and ISO parameters. It can be seen that the front impact parameters are closer to ISO, especially

Fig. 21. Comparison of side impact parameters and ISO parameters of A0 class vehicles.

Fig. 22. Comparison of side impact parameters and ISO parameters of A class vehicles.

Table 3. Comparison of impact parameters and ISO.

Impact parameter	Initial slope k_{EF} & k_{AB}	Late slope k_{CD} & k_{GH}	Peak A_{FG} & A_{BC}	Pulse width
A0 class vehicle frontal collision	Larger	Equal	Equal	Equal
A class vehicle frontal collision	Equal	Equal	Larger	Equal
A0 class vehicle side collision	Larger	Larger	Larger	Smaller
A class vehicle side collision	Larger	Larger	Equal	Smaller

the waveform pulse width. The side impact parameters are significantly different from ISO. The pulse width is small and the response time is advanced.

4.2. Discussion

In China, the national compulsory crash standard is performed by the full-width rigid barrier test, while ECE R94 offset deformable barrier test is usually conducted abroad. Thus, the ISO parameters are derived by the frontal offset deformable

barrier collisions, by contrast, the test conditions used in this paper are frontal rigid barrier collisions. For the same model, the peak acceleration of the offset collision test is smaller than the peak acceleration of the rigid barrier collision. Therefore, the average quality of the models participating in the ISO standard should be greater than that of the A0 class vehicles, in order to maintain the peak acceleration and the A0 class vehicles. Due to the small size of the front end structure of the A0 class vehicle, the collision process is short. The average trapezoidal waveform is shorter than the ISO in the pulse width. The slope of the collision curve is significantly larger than ISO. The peak value of the equivalent impact waveform of the A-class vehicle is higher than ISO, which is also consistent with the actual vehicle crash test conditions. Most of the domestic A-class vehicles are retrofitted on the basis of mature gasoline vehicles. The above two front collision working conditions will be balanced in structural performance design based on the C-NCAP star rating conditions. Therefore, the waveform characteristics are similar. From this, it can be further verified that the average model used by the ISO is close to the A-class vehicle in the Chinese market.

For the side impact, the impact parameters of the A0 class vehicle are significantly different from the ISO because of the quality of the test vehicle, the side wall structure and the space. Different from the frontal collision, the quality directly determines the impact response of the vehicle body in side impact. The smaller the mass, the greater the acceleration generated by the body when subjected to side impact. At the same time, the side wall structure has insufficient energy absorption, which will cause the vehicle body to accelerate too much. The average equivalent trapezoidal wave peak of the side impact of the A-class vehicle is close to ISO, and the time history is about 20 ms earlier than the average waveform in the ISO channel.

Therefore, the impact waveform used in the ISO standard uses the same time history and feature nodes for both the front and the side collision, which is obviously inconsistent with the actual vehicle collision response signal. Therefore, the front and side impact waveforms should be defined separately to achieve better simulation accuracy.

5. Conclusion

In this paper, for the A0-class and A-class new energy vehicles, the power battery shock waveform of the typical vehicle in the front and side collision modes is obtained. According to the waveform statistics, the average waveform of the corresponding power battery is obtained. The average waveform was processed by the equivalent trapezoidal wave and least squares method, and the characteristic values of the impact test waveforms of domestic A0 and A-class vehicles were obtained. The obtained waveform parameters are benchmarked with the ISO12405-3 battery dynamic test waveform, and the test parameters development process, differences

and causes are analyzed. The main conclusions are as follows:

- (i) A separate intensity impact channel should be used for the A0 class vehicle, because the A0 class vehicle has a large amount in China. Its response in collision conditions is quite different from that of A-class vehicles.
- (ii) Considering the response characteristics of new energy vehicles in the vehicle crash test, the power battery should be tested with a more severe impact waveform than the ISO standard.
- (iii) The impact waveform channel specified in the ISO standard does not consider the Chinese working conditions. It is unreasonable to use the same impact waveform for the front and side working conditions. Two independent waveforms for testing are recommended to use.

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