Investigation on Vibration Durability Test Method of Fuel Cell Stack Based on Vehicle

Zhen Wu
China Automotive Technology and Research Center Co., Ltd., Tianjin, China
Email: wuzhen@catarc.ac.cn

Shiyu Wu[1], Rongliang Liang[1,2], Ting Guo[1], and Fengling Gao[1]
[1] China Automotive Technology and Research Center Co., Ltd., Tianjin, China
[2] School of Mechanical Engineering, Tianjin University, Tianjin, China
Email: wushiyu@catarc.ac.cn, liangrongliang@catarc.ac.cn, guoting@catarc.ac.cn, gaofengling@catarc.ac.cn

Abstract—**The vibration spectra of the vehicle fuel cell stack under 8 kinds of strengthened roads in the test site are collected. And the corresponding fatigue damage spectra (FDS) of each road surface are calculated respectively. Then the total fatigue damage spectra are obtained by accumulating the FDS under all roads according to miner damage criterion. According to the durability target of vehicle fuel cell stack, based on the principle of consistent fatigue damage spectrum, this paper puts forward the method of formulating PSD, and then carries out bench vibration durability test, which can effectively strengthen the 108 h road vibration test. At the same time, in order to shorten the duration of bench test and achieve the purpose of accelerated test, the duration of each axle vibration test is compressed to 23h, and the limit response spectrum (ERs) generated by PSD of accelerated vibration test is less than the maximum possible response spectrum of 8 kinds of enhanced pavement impact response spectrum (SRS), so as to ensure that the accelerated vibration test of fuel cell stack will not produce unrealistic high load.**

Index Terms—**Fuel cell stack, Vibration spectrum, Fatigue damage spectrum, Shock response spectrum, Bench durability test**

I. Introduction

Fuel cell is a new type of power generation device, which can efficiently and environmentally convert the chemical energy stored in the fuel into electric energy. It has the advantages of high efficiency, low pollution, high power density, fast start-up and low operating temperature. It has become a new power source for automobiles. However, the development of fuel cell vehicles is restricted by the durability of fuel cell stacks. In order to promote the large-scale commercialization of fuel cell vehicles, it is urgent to improve the durability of fuel cell stacks [1].

Due to the variety of road conditions, the random vibration caused by uneven road surface will not only affect the mechanical structure of vehicle fuel cell stack, but also affect its performance. Therefore, the vehicle fuel cell stack should have good vibration durability, so as to ensure the reliability of the fuel cell system and the whole vehicle. In this paper, the vibration spectrum of vehicle fuel cell stack on the test field is collected by the real vehicle, and then the power spectral density (PSD) based on vibration acceleration is formulated to carry out bench durability test and acceleration test.

II. Analysis of Vibration Source of Vehicle Fuel Cell Stack

As the power source of automobile, the durability of vehicle fuel cell stack is very important. Vehicle fuel cell stack is composed of single cells through connection. Vibration and impact will have adverse effects on single cells, thus directly affecting the service life [2]. Due to the complex driving conditions, the changeable environment, climate and road conditions, the fuel cell stack must continue to bear the vibration and impact loads from the road when the vehicle is driving. The influence of this mechanical vibration mainly includes the following three aspects:

- The ride comfort of a car is directly affected by the bumpy condition of the road.
- Under a variety of complex operating conditions, fuel cell vehicles are not running at a constant speed for a long time. Especially under urban operating conditions, the vehicle changes under accelerated starting, braking, turning and idling conditions for a long time, which bring inertia impact to the fuel cell stack continuously.
- In case of traffic accident, extreme impact and extrusion will cause serious damage to the fuel cell stack. It may cause greater danger and bring hidden dangers to drivers and passengers.

III. Real Vehicle Enhanced Road Vibration Test and Treatment

A. *Real Vehicle Enhanced Road Vibration Spectrum Acquisition*

Due to the bench vibration durability test of vehicle fuel cell stack is mainly conducted on the 6-channel multi axis simulated vibration test bench of mast. Therefore, in

Manuscript received August 22, 2022; revised September 7, 2022.

doi: 10.18178/ijeee.10.1.14-18

the road vibration spectrum collection test of the whole vehicle, five acceleration sensors are arranged at the vehicle fuel cell stack and its mounting connected with the frame to measure the vibration acceleration signal. The location of acquisition measuring points is shown in Table I.

TABLE I. REAL VEHICLE ROAD VIBRATION SPECTRUM COLLECTION AND MEASUREMENT POINTS

Order	Location of measuring point	Type	Direction
1	Front of stack	Objective iteration	x,y,z
2	Left of stack	Monitoring control	x,y,z
3	Right of stack	Monitoring control	x,y,z
4	Left mount of stack	Objective iteration	x,y,z
5	Right mount of stack	Monitoring control	x,y,z

The real vehicle road vibration spectrum collection test is carried out on the strengthened and durable road of a test site. A cycle of measurement and collection includes 8 kinds of strengthened pavement. The test has been conducted for 5 times in total, and the length of each channel signal of the vibration spectrum of each test is about 1058s. The composition and driving speed of the strengthened roads in the test site is shown in Table II.

TABLE II. STRENGTHENED ROAD AND TEST SPEED IN THE TEST FIELD

Order	Road name	Length (m)	Speed (km/h)
1	Washboard road A	200	55
2	Washboard road B	200	55
3	Pothole Road	200	10
4	Bump road A	90	15
5	Bump road B	90	25
6	Boulder Road	200	18
7	Belgian Road	2500	20
8	Coarse asphalt road	400	60
Total		3880	--

B. *Vibration Spectrum Data Processing*

Through the statistical analysis of the measured dynamic response data of the strengthened road, the consistency between each test cycle data and the overall test statistical data is investigated to verify whether each cycle data has the statistical characteristics of ergodic, which is of great significance for the validation of the test [3]. The test validation is carried out accurately only after the data are correct. Therefore, the data is processed through the following aspects:

- Low pass filter processing: Low pass filtering can eliminate high-frequency interference signals and improve signal-to-noise ratio. The low-pass filter frequency is set with reference to the frequency range of pavement excitation. The frequency of strengthening pavement load is mainly within 50Hz, so the low-pass filter frequency is selected as 50Hz for processing.
- De singular value: Due to the voltage change of the test equipment, electromagnetic interference or abnormal vibration of the test system, singular values may be generated in the collected signals. These abnormal data of non actual load must be eliminated, otherwise it will have a great impact on the estimation of the actual load and the durability life of the fuel cell stack [4].
- Remove trend items: Due to external interference and system reasons, some load signals often deviate from the baseline. The process of deviation from the baseline over time is called trend term. The data channels that generate trend items should be removed before they can be used normally. In this paper, the dynamic mean method is used to remove them.

Through the above methods, the processed time domain data is shown in Fig. 1 (taking Belgium road as an example). Then, the corresponding time domain data of the five tests under eight kinds of enhanced roads are statistically analyzed in amplitude range and spectrum. The results show that the statistical values of amplitude range and spectrum characteristics in each test cycle are basically consistent. Therefore, the data of one cycle is selected as the target response data.

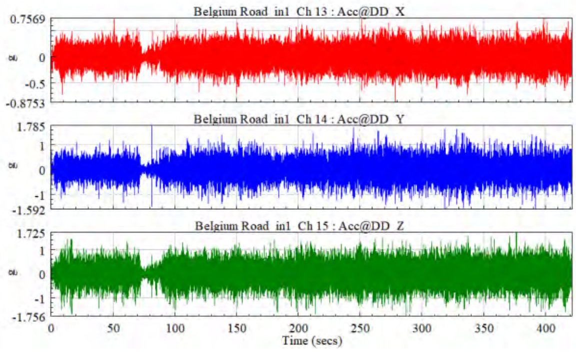

Figure 1. Time domain data of fuel cell stack (Belgium Road).

IV. BENCH DURABILITY TEST AND ACCELERATED TEST METHOD FOR FUEL CELL STACK

A. *Test Data Preparation*

Due to the time-domain data represent the relationship between acceleration data and time, it is not possible to directly drive the bench for test. The bench vibration durability test needs to use power density spectrum (PSD). Therefore, in this paper, the shock response spectrum (SRS) and fatigue damage spectrum (FDS) are calculated by using time domain data, and PSD is obtained to carry out the bench vibration durability test of fuel cell stacks.

1) *Shock response spectrum calculation*

The impact response spectrum, also known as "impact spectrum", refers to the maximum response value of each single degree of freedom system as a function response curve corresponding to the natural frequency of the system when the impact excitation is applied to a series of linear, single degree of freedom spring and mass systems [5].

By using ncode software, the vibration spectrum data of the front side of the fuel cell stack are calculated under 7 kinds of test site reinforced pavement and 1 kind of coarse asphalt pavement. Taking Belgium road as an example, the impact response spectrum of fuel cell stack is shown in Fig. 2.

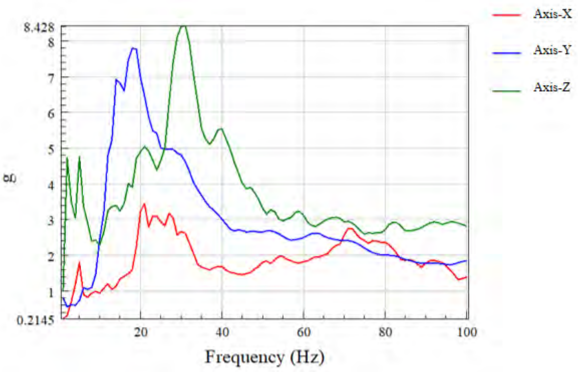

Figure 2. Shock response spectrum (Belgium Road).

At the same time, the impact response spectra under the strengthened road surface of the eight test sites are calculated according to the maximum value of the histogram data through the schedulecreate module.The SRS envelope of the fuel cell stack under the strengthened road surface of the eight test sites is obtained, which represents the SRS maximum possible response spectrum of the bench test. As shown in Fig. 3.

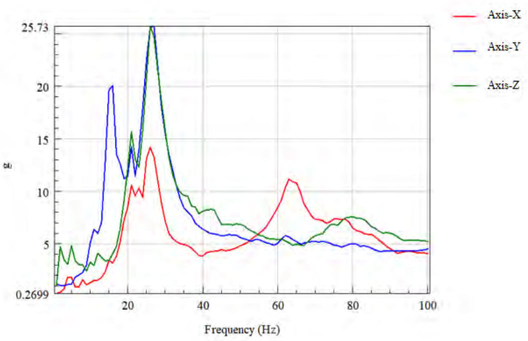

Figure 3. Maximum possible response spectrum of SRS.

2) Fatigue damage spectrum calculation

Fatigue damage spectrum is a random vibration spectrum based on Miner damage criterion. Fatigue damage accumulates over time until the damage reaches the limit value. Therefore, the fatigue damage spectrum is used to characterize the damage effect of this signal on the structure [6]. In order to complete the durability test verification of fuel cell stack on the bench, it is necessary to calculate the fatigue damage spectrum under each road surface as the boundary condition of the test.

Through the analysis and calculation of impact response spectra of 8 kinds of strengthened pavement in the test site, the SRS data corresponding to 8 kinds of strengthened pavement in the test site have been included. At the same time, using the same time-domain data as SRS calculation, the fatigue damage spectra of fuel cell stacks under 8 strengthened roads are calculated respectively. Taking Belgium road as an example, the fatigue damage spectrum of fuel cell stack is shown in Fig. 4.

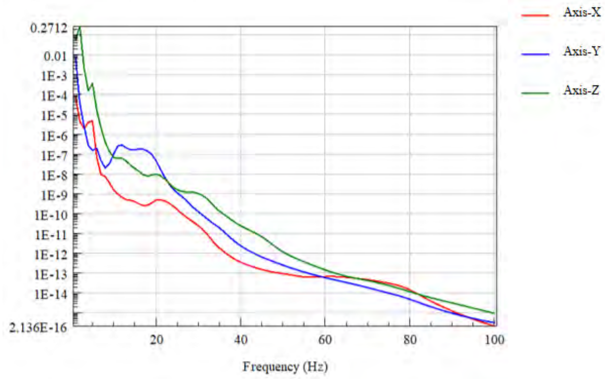

Figure 4. Fatigue damage spectrum (Belgium Road).

B. Test Method for Bench Vibration Durability of Fuel Cell Stacks

In the data preparation stage, a total of 16 data files can be used, and then PSD of bench vibration durability test is compiled based on the durability target of fuel cell vehicles. The assessment cycle requirements of the fuel cell stack used in the test field on eight enhanced roads is shown in Table III. The cumulative test duration of each axis is 108h.

TABLE III. DURABILITY TEST REQUIREMENTS FOR FUEL CELL STACKS

Order	Road name	cycle-index	Cumulative duration (h)
1	Washboard road A	1000	4
2	Washboard road B	1000	4
3	Pothole Road	500	10
4	Bump road A	1000	6
5	Bump road B	1000	3.5
6	Boulder Road	1000	11
7	Belgian Road	500	62.5
8	Coarse asphalt road	1000	7
Total		--	108

According to miner damage rule, the fatigue damage spectra under multiple enhanced road conditions are accumulated to obtain the total fatigue damage spectrum under a complete cycle. The accumulated total fatigue damage spectrum represents the cumulative damage to the fuel cell stack after the bench test is completed. Therefore, according to the cycle times requirements in Table III, the fatigue damage spectra of 8 kinds of pavements are summed according to the histogram data by using the schedulecreate module of ncode software, and the total fatigue damage spectra are shown in Fig. 5.

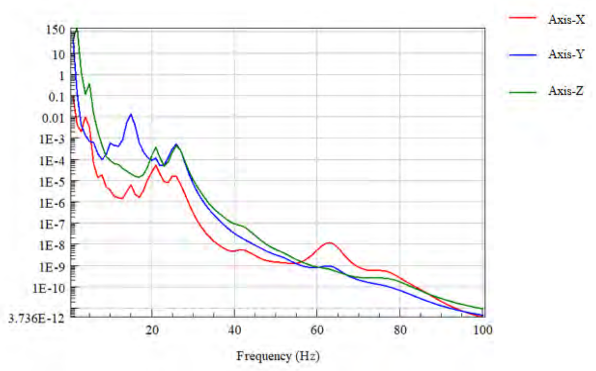

Figure 5. Total fatigue damage spectrum.

The principle of carrying out bench vibration durability test is that the failure mode or failure mechanism in the bench test of fuel cell stack shall be consistent with the failure mode or failure mechanism under the enhanced road test in the test site [7]. Therefore, the equivalent total fatigue damage spectrum is required for the driving PSD used in the bench vibration durability test of fuel cell stack. In this paper, according to the requirements of test cumulative duration in Table 3, the total fatigue damage spectrum curve in Fig. 4 is used to set the total durability test duration of 108h through the test synthesis method of ncode software, so as to obtain the PSD used to carry out the fuel cell stack bench vibration durability test, as shown in Fig. 6. Based on this, the vibration durability tests of fuel cell stacks in X, y and Z directions on the bench can be carried out respectively.

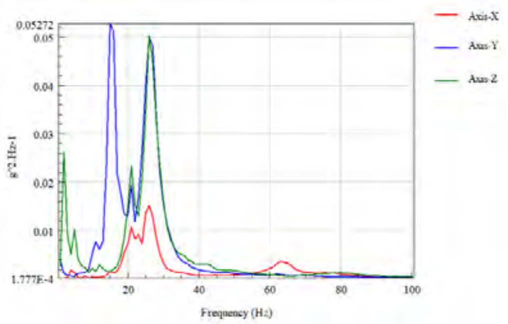

Figure 6. Vibration endurance test PSD.

C. *Accelerated Vibration Durability Test Method for Fuel Cell Stacks*

According to the above bench vibration durability test method, the test failure mode or failure mechanism of fuel cell stack under 8 kinds of reinforced pavement in the test field can be simulated equivalently in theory on the premise that the total fatigue damage spectrum remains the same.

However, the bench vibration test of fuel cell stack requires 108h for each axis and 324h for the total time. Therefore, in order to shorten the test cycle, achieve the purpose of accelerated test, and ensure that the fuel cell stack still has the same fatigue damage distribution and failure mechanism under the accelerated test spectrum and the load spectrum running on the enhanced road of the test site. The test synthesis module is used to continuously compress the duration of the durability test, and the total fatigue damage distribution generated by the accelerated test spectrum is continuously compared with the total fatigue damage spectrum in Fig. 4. The results show that when the vibration duration of each axis is compressed to the shortest 23h, the two continue to remain consistent, and the test duration is shortened by about 79%. PSD of accelerated vibration durability test is shown in Fig. 7.

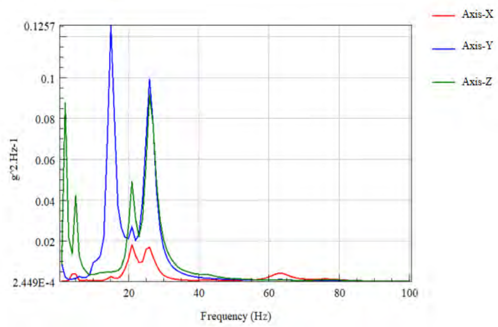

Figure 7. Accelerated vibration durability test PSD.

Fig. 7 shows that the y-axis energy of PSD in the 23h accelerated vibration durability test of each axis increases, and the maximum value changes from 0.0527 to 0.1257. In order to verify that the fuel cell stack will not generate high load that does not conform to the actual situation when the accelerated PSD is used for the test, the extreme response spectrum generated by the accelerated vibration durability test PSD is compared with the maximum possible response spectrum of SRS of the fuel cell stack shown in Fig. 5, and the results are shown in Fig. 8.

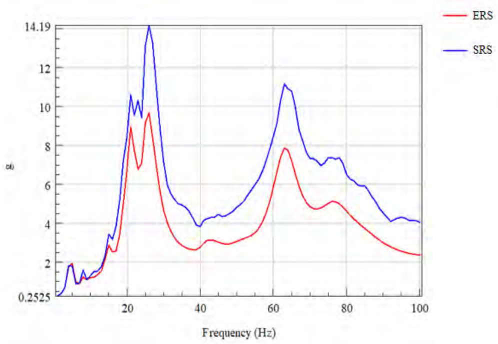

Figure 8. Comparison diagram of ESR and SRS.

Fig. 8 shows that the ERS spectrum generated by the PSD in the accelerated vibration durability test is less than the maximum possible response spectrum of SRS as a whole, indicating that the PSD in the accelerated vibration durability test will not have high load that does not conform to the actual situation. Therefore, the bench accelerated vibration durability test of fuel cell stack can not only effectively simulate the total fatigue damage spectrum of the road in the test field, but also greatly accelerate the test progress, which is of great significance for the durability test.

V. Conclusion

In this paper, the vibration test and bench durability test of fuel cell stack on the strengthened road surface of the test field are investigated. The main conclusions are as follows:

- Due to the complex driving conditions, fuel cell vehicles is influenced the vibration and impact loads caused by road roughness. Therefore, the real vehicle data acquisition of fuel cell stack on the enhanced road of the test site can provide accurate data input for the bench vibration durability test.
- In order to carry out the bench vibration durability test verification of fuel cell stacks, the PSD is compiled based on the method of equivalent test field strengthening the total fatigue damage spectrum (FDS) produced by fuel cell stacks under roads, which can effectively strengthen the 108h vibration durability test of pavement.
- In order to shorten the vibration durability test cycle of the fuel cell stack, the minimum test duration of each axis is reduced to 23h, which is about 79% shorter and consistent with the total fatigue damage spectrum. At the same time, the verification shows that the PSD of accelerated vibration durability test will not produce unrealistic high load on the fuel cell stack.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Wu Zhen conducted the research of Fatigue durability mechanism and analyzed the test data.

Wu Shiyu wrote the paper and analyzed the test data.

Liang Rongliang and Guo Ting are responsible for the design of test scheme.

Gao Fengling is responsible for the establishment of bench test.

References

[1] C Wang, S. Wang, J. Zhang *et al.*, "The durability research on the proton exchange membrane fuel cell for automobile application," *Progress in Chemistry*, vol. 27, no. 4, pp. 424-435, 2015.

[2] X. Feng, M. Huang, P. Wen *et al.*, "Development and prospect of fuel cell used by vehicle," *New Chemical Materials*, vol. 41, no. 1, pp. 1-4, 2013.

[3] L. Zhang, Y. Si, and Z. Yu, "Investigation into road simulation experiment of powertrain and its key components of a fuel cell passenger car," *Journal of Tongji University(Natural Science)*, vol. 37, no. 2, pp. 244-248, 2009.

[4] H. Wang, J. Wang, and N. Wang, "Combined application of amplitude threshold and gradient threshold on abnormal load omitting," *Journal of Vibration, Measurement and Diagnosis*, vol. 32, no. 3, pp. 387-391, 2021.

[5] M. Gao, C. Shi, and Y. Wang, "Research on the analysis method of shock response spectrum," *Science and Technology Vision*, vol. 28, pp. 117+194, 2012.

[6] J. Lu, H. Li, and X. Wang, "Research on vibration fatigue accelerated test of battery pack," *Automobile Applied Technology*, vol. 18, pp. 12-14, 2019.

[7] H. Chai, T. Zhang, J. Chen *et al.*, "Design and verification of fuel cell vehicle power system test platform," *Automobile Technology*, no. 1, pp. 25-30, 2019.