Research on Torque Characteristics of Clamping Bolts for PEMFC Stack under Strengthened Durability Vibration

Yanyi Zhang\textsuperscript{1, a}, Dong Hao\textsuperscript{1, b}, Renguang Wang\textsuperscript{1, c} and Yongping Hou\textsuperscript{2, *}

\textsuperscript{1}China Automotive Technology and Research Centre Co. Ltd, Tianjin, China
\textsuperscript{2}School of Automotive Studies, Tongji University, Shanghai, China

*Corresponding author e-mail: yphou@tongji.edu.cn, \textsuperscript{a}zhanyanyi@catarc.ac.cn, \textsuperscript{b}haodong@catarc.ac.cn, \textsuperscript{c}wangrenguang@catarc.ac.cn

Abstract. To investigate the bolt torque attenuation feature of PEMFC stack under static test and vibration test conditions, 2-hour static test and 300-hour enhanced road vibration test were carried out in turn. The results show that the attenuation of bolt torque are related to their locations during the static test, also the attenuation of bolt torque is obviously related to their locations during the 300-hour vibration test. Moreover, the test results also show that there are different regularities in different vibration test periods.

1. Introduction
Proton exchange membrane fuel cell (PEMFC) is composed of multiple single cells in series and usually clamped with bolts. The degree of tightness is generally characterized by the size of the bolt torque. Reasonable, stable and consistent bolt torque has important influence on the performance and durability of PEMFC stack, on one hand, deficient torque may lead to gas leakage, higher contact resistance and lower output power; on the other hand, excessive torque will condense the gas diffusion layer and minify the porosity and gas permeability, which will affect the efficiency of PEMFC stack significantly. In extreme case, it will crush the stack and lead to the failure [1-5].

Selamet studied the relationship between the bolt torque and efficiency of the PEMFC and came to the conclusion that the optimum efficiency of different proton exchange membrane made of diverse materials is in need of various torque [6]; Mallick drew a conclusion that both excessive and deficient torque will bring down the performance of the PEMFC by the means of the electrochemical impedance spectrum (EIS) [7]; With the aid of modal simulation of harmonic analysis, Deshpande et al. detected hydrogen leakage around the washer of the fuel cell when free vibrations that coincide with the natural frequency [8]; Hou, by virtue of polarization curve during the vibration test carried on strengthen road, presented a decline of open circuit voltage and an increase of ohmic resistance due to the vibration [9-10]; Rajalakshmi analyzed the influence of the sinusoidal vibration exerted on the PEMFC stack and stated that the bolt torque and power output of the PEMFC stack were both damped after the vibration [11]; Pestrak conducted a mechanical fatigue experiment on the Membrane Electrode Assembly (MEA) and proton exchange membrane via loading pressured bubble and found that the MEA was more likely to come leakage earlier than proton exchange membrane under the same load level [12-14]; Application of the finite element method, Ahmed et al. investigated the effect of thickness, young's modulus and density of the material to the modal and natural frequency of the
MEA, providing some reference of the PEMFC stack durability under mechanical vibration [15]; Banan applied vibration load on the MEA in the form of numerical simulation, observing stripping between proton exchange membrane and catalytic layer interface [16]. All these references above mentioned show that vibration can result in the attenuation of the bolt torque, and then affected the performance and durability of the PEMFC stack. However, what is the amplitude of bolt torque attenuation and what is the relationship between the bolt torque of the attenuation and the location, there is no systematic report on open literatures.

This paper focuses on the bolt torque changing features by static and durability vibration test respectively. After preloading the stack, a static test was carried out and then a strengthen road durability vibration test would be proceeded.

2. Test conditions and test equipment

2.1. Test sample of the PEMFC stack

The sample PEMFC stack was shown in Fig.1 with geometric size 390 mm (L) × 235 mm (W) × 275 mm (H) and weight of 30.9 kg, rated power of 9 kW. The fore end plate of the PEMFC stack, with the import and export, was made of composite material, while aluminum alloy for the rear plate of the fuel cell. The PEMFC stack, piled up by 90 single cells in series, was clamped with 8 sets of screw-and-nut assemblies between the fore end plate and the rear end plate. The effective activation area of the single cell was 250 cm$^2$, with the corresponding rated current density 600 mA/cm$^2$. Representatively, there was a silicone rubber gasket between the rear end plate (with no import and export) and the last bipolar plate.

![Figure 1. The explode diagram of the PEMFC stack structure](image)

(1 Silicone rubber gasket; 2 Fore plate; 3 Rear plate; 4 Connecting screw rod; 5 Current collector; 6 Bipolar plate; 7 MEA; 8 Insulating plate; 9 Silicone rubber gasket)

The material parameters of each component of the PEMFC stack shown in figure.1 were listed in table 1.
### Table 1. Material parameters of the PEMFC stack

| Component            | Material            | Modulus of elasticity (MPa) | Poisson ratio | Density (kg/m³) |
|----------------------|---------------------|-----------------------------|---------------|-----------------|
| Rubber gasket        | Vulcanized rubber   | 6                           | 0.49          | 1150            |
| Fore plate           | ABS                 | 2000                        | 0.394         | 1100            |
| Rear plate           | Aluminium alloy     | 69000                       | 0.33          | 2800            |
| Bolt                 | C45E4               | 200000                      | 0.3           | 7800            |
| Current collector    | Phenolic resin      | 13500                       | 0.3           | 1500            |
| Bipolar plate        | Graphite            | 10000                       | 0.25          | 2160            |
| MEA                  | Carbon paper        | 60                          | 0.33          | 440             |
| Insulating plate     | Copper              | 100000                      | 0.33          | 8940            |

2.2. Test equipment

The vibration test of the PEMFC stack was conducted on the Six-channel Multi Axial Simulation Table (MAST) as shown in Fig.2.

![Figure 2. Six-channel multi axial simulation table](image)

Details introductions of the MAST were consulted the assigned references [17-20]. The MAST excitation to the PEMFC stack acts in the form of displacement. Its time-domain displacement drive spectrums were given in Fig.3.

![Figure 3. Driving signal of displacement acted by the vibration test bench](image)
2.3. Test Procedure and Results
Before the static test, the PEMFC stack was screwed with eight bolts with torque of 10 $N \cdot m$ for one bolt; 2h later, the bolt torque was measured and recorded respectively. After the static test, the PEMFC stack was fixed at the MAST and carried for 300h strengthen road durability vibration test. During the vibration test, the torque of 8 bolts were measured and recorded every 50h. The 8 bolts were numbered from 1–8 for the convenience, and the tagged rear plate was shown in figure 4.

![Figure 4. 8 serial numbers labeled on the rear plate](image)

3. The research of the bolt torque change feature

3.1. The research of the bolt torque change feature under static condition
After the 2h static test with initial torque of 10 $N \cdot m$, it was found that the attenuation values of 8 bolts are inconsistent. In order to investigate the change characteristics of the bolt torque, the changes were plotted in figure 5.

![Figure 5. The torque attenuation condition after 2h static test](image)

As shown in Fig.5, the attenuation of torque of 8 bolts differs from each other with certain regularities. That is: the numbers labeled with 1, 4, 5, 8 attenuated fast, while numbers tagged 2, 3, 6, 7 attenuated slowly. According to Fig.4, bolts numbered with 1, 4, 5 and 8 were located just at the four corners of the rear plate, meanwhile numbers of 2, 3, 6 and 7 on the bolts were located just inside of
the plate. Therefore, the 8 bolts were divided into inner group (2, 3, 6, 7) and outer group (1, 4, 5, 8) for analyzing. After static stayed for 2 hours, torque of external bolts damped with great amplitude, with the maximum residual value $4.6 \, N\cdot m$, and the minimum residual value $3.5 \, N\cdot m$; while torque of internal bolts damped with slight amplitude, with the maximum residual value $9.5 \, N\cdot m$ and the minimum $7.2 \, N\cdot m$.

For accurate analysis of internal and external bolt torque of 2h static attenuation test, the formula was defined as follows:

$$k_i = \frac{T_{ib} - T_{if}}{T_{ib}}$$  \hspace{1cm} (1)

In Eq. (1), $k_i$ is the bolt torque attenuation rate of number $i = 1, 2, 3, 4, 5, 6, 7, 8$; $T_{ib}$ is the initial torque of number $i$ bolts before static test; $T_{if}$ is the torque of number $i$ bolts after 2h static stay.

The torque attenuation rate of each bolt drawn in Fig.5 were calculated and shown in Table 2 according to Eq. (1).

|   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
| $k_i$ | 0.6 | 0.28| 0.20| 0.54| 0.57| 0.25| 0.05| 0.65|

Table 2. The attenuation rate after 2h static test

The attenuation rates of the PEMFC stack during the static test were presented in Table 2. The attenuation rates of $k_1, k_4, k_5, k_8$, corresponding to external bolts of 1, 4, 5, 8, are 0.6, 0.54, 0.57, 0.65; while $k_2, k_3, k_6, k_7$, corresponding to internal bolts of 1, 4, 5, 8, are 0.28, 0.20, 0.25, 0.05. The following formula was defined:

$$\bar{k} = \frac{1}{n} \sum_{i} k_i$$  \hspace{1cm} (2)

According to Eq. (2), when $i = 1, 4, 5, 8$, $n = 4$, the average attenuation rate of the external bolt torque $\bar{k}_{out}$ is 0.59; when $i = 2, 3, 6, 7$, $n = 4$, the average of the internal bolt torque attenuation rate $\bar{k}_{in}$ is 0.195; while $i = 1, 2, 3, 4, 5, 6, 7, 8$, $n = 8$, the average of overall bolt torque attenuation rate $\bar{k}_{overall}$ is 0.3925. The torque attenuation rates of external, internal and overall bolts during static test were presented in figure 6.
According to Fig.6, the following two conclusions can be drawn:

1) After the static test, the attenuation rates of bolt torque were closely related to the locations, there were two different kinds of rates: the attenuation rate of the internal bolts and the attenuation rate of the external bolts. On the whole, the average attenuation rate of external torque is greater than the internal average torque attenuation rate.

2) From the testing data of this work, the external average torque attenuation rate is 0.59, the internal average torque attenuation rate is 0.195, the external rate is about 3 times as the internal one, and the overall average torque attenuation rate is 0.3925.

3.2. The research of the bolt torque variation feature in the process of 300h durability vibration test

3.2.1. The global analysis of the torque variation during the 300h durability vibration test. To find that bolt torque vary detail during the process of vibration, a test of 300h durability vibration was carried out on the PEMFC stack after 2h static test. The bolt torque, gauged every 50h during the durability vibration test, was represented in figure 7.
As shown in figure 7, the torque attenuation is obviously relevant to the location of the bolt during the process of 300h vibration, namely the internal attenuation rate significantly differs from the external attenuation rate. The torque of the four inner bolts and the four outer bolts, gauged in the 300h vibration test, were linear fitted respectively. The results were presented in figure 8 and figure 9.

![Figure 8. External bolt torque variation conditions during the vibration test](image1)

![Figure 9. Internal bolt torque variation condition during the vibration test](image2)

The attenuation rates shown in table 3 were the absolute slope values of the the linear fitted lines for eight bolts respectively.

| i  | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
|----|-------|-------|-------|-------|-------|-------|-------|-------|
| $k_i$ | 0.00471 | 0.00527 | 0.00779 | 0.00577 | 0.00589 | 0.0055 | 0.007 | 0.00244 |
To get the relationship between the attenuation feature of the bolt torque and the the bolt location, the quantitative analysis of the relationship between the internal bolt attenuation rate and external bolt attenuation rate was completed, and got the external average attenuation rate by equalizing the 1, 4, 5, 8 four bolts torque attenuation rate, finally the average rate of 0.0047 in the process of 300h durability vibration test was drawn. Alternately, the internal average attenuation rate was calculated by equalizing the 2, 3, 6, 7 four bolts torque attenuation rate, and eventually get the average rate of 0.00621 in the process of 300h durability vibration test. The above data show that in the process of 300h durability vibration test, the internal average attenuation rate is greater than the external one, and the inner bolts torque average attenuation rate is 1.32 times than the outside one. This is because the internal bolts torque is greater than the external torque value after 2h static test. That means, at the beginning of the vibration test, the attachment between the internal bolts and the rear plate is more tightened than the attachment between the external bolts and the rear plate. The greater of the torque, the greater of the attenuation rate, and so the internal bolts torque attenuation rate is greater than the external one.

3.2.2. The analysis of each time period of the torque variation during the 300h durability vibration test. Basing on results of linear fitting of the torque for the 300h durability vibration test, the torque attenuation condition shows some regularity with the location of the bolts. There were two attenuation features: the external bolt torque attenuation rate and internal bolt torque attenuation rate. For more deep research of the variation of torque during the 300h vibration test, elaborative observation into the torque during the process of the vibration test was conducted, and find that the torque presents different change of rules during 0~100h, 100h~200h and 200h~300h. So the process of 300h vibration test was divide into three stages of 0~100h, 100h~200h and 200h~300h. The torque data was linear fitted for different time periods respectively, as shown in Fig.10.

![Figure 10. The torque and linear fitted results for different time stages](image)

From Fig.10, the torque of eight bolts of the three stages during the vibration test present a declining trend on the whole, but they behave in a variety of characteristics during different stages. In order to get the attenuation features of different bolts torque, the slopes of bolt torque fitting lines of each phase was calculated and the attenuation rates were defined by the absolute value of the corresponding slopes, which were listed in table 4.
Table 4. Torque attenuation rates of each bolt with vibration in three stages

|     | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
|-----|-------|-------|-------|-------|-------|-------|-------|-------|
| $k_{11}$ | 0.0046 | 0.008 | 0.01  | 0.004 | 0.004 | 0.015 | 0.011 | 0.0014 |
| $k_{12}$ | 0.0072 | 0.0076 | 0.001 | 0.0096 | 0.0108 | 0.0018 | 0.009 | 0.003 |
| $k_{13}$ | 0.0015 | 0.0008 | 0.013 | 0.0012 | 0.0 | 0 | 0.005 | 0.0036 |

In table 4, that the torque attenuation rates of No.5 bolt and No.6 bolt are zero in the third stage, namely, the bolt torque of 5 and 6 remain unchanged in the third stage. The torque attenuation rates in the first and second phases of bolt 5, 6 and the torque attenuation rates of bolt 1, 2, 3, 4, 7, 8 during the three phases are positive, namely the bolt torque has a decreasing trend.

As there were differences between the two groups of internal and external attenuation rates of bolts torque, the changes of torque values can be divided into internal and external groups of external and internal for more detailed analysis. The average attenuation rate of three stages of external bolts torque $\bar{k}_{out}$, as shown in Table 5, was defined by the three attenuation rates of each phase of the external bolts torque respectively.

Table 5. Individual and average torque attenuation rates of external bolts in three stages

|     | 1     | 4     | 5     | 8     | $\bar{k}_{out}$ |
|-----|-------|-------|-------|-------|-----------------|
| $k_{11}$ | 0.0046 | 0.004 | 0.004 | 0.0014 | 0.0035 |
| $k_{12}$ | 0.0072 | 0.0096 | 0.0108 | 0.003 | 0.0076 |
| $k_{13}$ | 0.0015 | 0.0012 | 0 | 0.0036 | 0.0016 |

As seen from Table 5, the torque of third stage attenuation rate of No.5 bolt is zero, namely, the torque of No.5 bolt remains unchanged during the third stage. The torque of first and second stage of No.5 bolt and the torque of No.1, 4, 8 bolts of the three phases are decreasing, which means the torque present the trend of declining, the average attenuation rates of the four external bolts in the three stages of vibration are 0.0035, 0.0076, 0.0016 respectively. For convenience, the individual and average torque attenuation rates of external bolts of three stages during vibration were represented as shown in Fig.11.

![Figure 11](image_url)

**Figure 11.** The individual and average torque attenuation rates of external bolts

As displayed in Fig.11, during the three stages, the torque attenuation rate of No. 1, 4, 5 bolts of the
second phase are the maximum, the first stage takes the second place, the third stage are the minimum, the torque attenuation rates of the three bolts of No.1, 4, 5 in the second phase are major, the torque attenuation rate of No.8 bolt presents the tendency of increasing during the three stages. The average torque attenuation rates in the second stage of external bolts is the largest, followed by the first stage, and the third stage is the minimal.

The average torque attenuation rates of the three stages of internal bolts $k_{in}$, as shown in Table 6, were defined by the three attenuation rates of the internal individual bolts torque respectively.

| Table 6. Individual and average torque attenuation rates of internal bolts in three stages |
|---------------------------------|---------------|---------------|---------------|---------------|
| $k_{i1}$ | 2           | 3           | 6           | 7           | $\bar{k}_{in}$ |
| 0.008   | 0.01        | 0.015       | 0.011       | 0.011       |
| $k_{i2}$ | 0.0076      | 0.001       | 0.0018      | 0.009       | 0.00485       |
| 0.0008  | 0.013       | 0.005       | 0.0047      |

From Table 6, the torque attenuation rate of bolt No.6 in the third stage is zero, namely, the torque of No.6 bolt remains invariable during the third stage. The torque attenuation rates of No.6 bolt in the first and second stage and the torque attenuation rates of No.2, 3, 7 bolts of the three phases are positive, that means the torque present a trend of declining. The average torque attenuation rates of the four external bolts in the three stages during vibration test are 0.011, 0.00485, 0.0047 respectively. For convenience, the individual and average torque attenuation rates of internal bolts of three stages during vibration were rearranged, as shown in Fig.12.

Figure 12. The individual and average torque attenuation rates of internal bolts

As displayed in Fig.12, during the three stages, the torque attenuation rates of No. 2 bolt are positive and the value of the attenuation rates are declining, namely, the torque of No.2 bolt presents the tendency of downtrend but the trend of amplitude is decreasing during the three stages. The torque attenuation rate of No.3 bolt in the third phase is the maximum, the first stage takes the second place, the second stage is the minimum. The torque attenuation rates of No.6 and 7 bolts present the tendency of decreasing during the three stages or rather the torque attenuation rates of No.6 of the third phase is zero, namely, the torque of No.6 bolt keeps stable during the third stage. All in all, during the three stages of vibration tests, the average torque attenuation rates of internal bolts present the tendency of diminution.

The torque attenuation rates of overall bolts of the three phases are 0.0075, 0.00625, 0.00317
respectively, which were calculated using Equation (2). The average torque attenuation rates of the external, internal and overall bolts of the three stages were turned into a column graph, as shown in Fig.13.

![Graph showing average torque attenuation rates](image)

**Figure 13.** Average torque attenuation rates of the external, internal and overall bolts in three stages

Seen from Fig.13, during the three stages of the external bolts torque attenuation rate, the second stage is the maximum, the first stage takes the second place, the third stage is the minimum. Regarded as one in the first stage, the attenuation rate of the second phase is 217.1% of the first stage, that means the second phase is as 2.172 times as the first stage, while the attenuation rates of the third phase is 45.7% of the first stage. The average torque attenuation rates of three stages of internal bolts present the tendency of diminution, if the torque attenuation rate of the first stage is regarded as one, while the attenuation rates of the second phase is 44.1% of the first stage, the attenuation rates of the third phase is 42.7% of the first stage.

Compared external bolt torque and internal bolt torque, they show different features of torque attenuation rates during the three stages of the vibration test, the torque attenuation rates of external bolt present the rule of increasing at first and then decreasing, while the torque attenuation rates of internal bolt present the rule of decreasing trends. The feature of the torque attenuation rates of external bolt, which increased at first and then decreased, is related to the disparity of the internal and external bolt torque, for the reason that the torque values will produce an effect on each other\(^{(21)}\). The feature of the torque attenuation rates of the internal bolt present decreasing trend is related to processes of the screw-pairs of bolt and screw nut, which goes through the plastic deformation and fretting wear\(^{(22, 23)}\).

The average torque attenuation rates of three stages of overall bolts present the tendency of diminution, if the torque attenuation rate of the first stage is regarded as one, while the attenuation rates of the second phase is 83.3% of the first stage, the attenuation rates of the third phase is 42.3% of the first stage.

4. **Conclusion**

In this paper, 2h static test and 300h strengthen durability vibration test were carried out in turn to study the bolt torque attenuation regularities. The conclusions are presented as follows:

1) In the process of 2h static test, the bolt torque, interrelated in the location of the rear plate, display a variety of attenuation rate. More generally, two kinds of attenuation rate, the external and internal attenuation rates, are 0.59 and 0.195 respectively. The external one, about three times as the internal one, together with the internal one, combines the overall attenuation rate of 0.3925.
2) During the process of durability vibration test, the bolt torque attenuation rate, relevant to the bolt position of the rear plate, are also divided into two groups of external bolts and internal bolts. In terms of the tested PEMFC stack, the average torque attenuation rate of internal bolts is 1.32 times as the other.

3) During the process of durability vibration test, the bolt torque attenuation rates vary at different phases. For the external attenuation rate, the second stage is the maximum, the first stage is the lesser, the third stage is the minimum; for the internal, the first stage is the maximum, following the second stage, and the third stage is the minimum; while for the overall, the bolt torque attenuation rates decrease in sequence during three stages.

Acknowledgments
Special thanks are due to the National Key Research and Development Program of China (Project No. 2017YFB0103100), National Key Research (Project No. 2018YFE0105400) and Tianjin Municipal Science and Technology Commission Program (Project No. 17ZXFWGX00040) for supporting authors’ research.

References
[1] WU Cheng-wei, LIN Peng. Design and analysis of optimal clamping force of fuel cell stacks [J]. Chinese Journal of Power Sources, 2013, 37 (09): 1546 ~ 1549.
[2] ZHOU P, WU C W, MA G J J. Influence of clamping force on the performance of PEMFCs [J]. Journal of Power Sources, 2007 (163): 874 ~ 881.
[3] AHMED D H, SUNG H J, BAE J. Effect of GDL permeability on water and thermal management in PEMFCs II: Clamping force [J]. International Journal of Hydrogen Energy, 2008 (33): 3786 ~ 3800.
[4] HOU Y, SHEN C, HAO D, et al. A dynamic model for hydrogen consumption of fuel cell stacks considering the effects of hydrogen purge operation [J]. Renewable Energy, 2014 (62): 672 ~ 678.
[5] Hou Yongping, Hao Dong, Shen Jianping, Li Ping, Zhang Tao, Wang Hong. Effect of strengthened road vibration on performance degradation of PEM fuel cell stack. International Journal of Hydrogen Energy. 2016, 41 (9): 5123 ~ 5134.
[6] Selamet, O.F., M.S. Ergoktas. Effects of bolt torque and contact resistance on the performance of the polymer electrolyte membrane electrolyzers [J]. Journal of Power Sources, 2015 (281): 103 ~ 113.
[7] Mallick, R.K., et al. Analysis of the clamping effects on the passive direct methanol fuel cell performance using electrochemical impedance spectroscopy [J]. Electrochimica Acta, 2016 (215): 150 ~ 161.
[8] Deshpande, J., T. Dey, P.C. Ghosh. Effect of Vibrations on Performance of Polymer Electrolyte Membrane Fuel Cells [J]. Energy Procedia, 2014 (54): 756 ~ 762.
[9] Hou, Y., et al. An investigation of characteristic parameter variations of the polarization curve of a proton exchange membrane fuel cell stack under strengthened road vibrating conditions [J]. International Journal of Hydrogen Energy. 2012, 37 (16): 11887 ~ 11893.
[10] Hou Yongping, Hao Dong, Shen Caoyuan, Shao Zhongying. Experimental investigation of the steady-state efficiency of fuel cell stack under strengthened road vibrating condition. International Journal of Hydrogen Energy. 2013, 38 (9): 3767 ~ 3772.
[11] Rajalakshmi, N., S. Pandian and K.S. Dhathathreyan. Vibration tests on a PEM fuel cell stack usable in transportation application. International Journal of Hydrogen Energy [J]. 2009, 34 (9): 3833 ~ 3837.
[12] Pestrak M, Li Y Q, Case S W, et al. The Effect of Mechanical Fatigue on the Lifetimes of Membrane Electrode Assemblies. Journal of Fuel Cell Science and Technology. 2010, 7 (4).
[13] Li Y, Dillard D A, Case S W, et al. Fatigue and creep to leak tests of proton exchange membranes using pressure-loaded blisters. Journal of Power Sources. 2009, 194(2): 873~879.
[14] Dillard D A, Ellis M W, Lai Y, et al. On the Use of Pressure-Loaded Blister Tests to Characterize the Strength and Durability of Proton Exchange Membranes. Journal of Fuel Cell Science and Technology. 2009, 6 (3): 3104.

[15] Ahmed H E U, Banan R, Zu J W, et al. Free vibration analysis of a polymer electrolyte membrane fuel cell. Journal of Power Sources. 2011, 196(13): 5520 ~ 5525.

[16] Banan R, Bazylak A, Zu J. Effect of mechanical vibrations on damage propagation in polymer electrolyte membrane fuel cells. International Journal of Hydrogen Energy. 2013, 38 (34): 14764 ~ 14772.

[17] MTS Co. Ltd. MAST system homepage. Accessed From: http://www.mts.com/en/vehicles/component/MAST/index.asp.

[18] MTS Systems Corporation, “Standard Multi-Axial Simulation Table (MAST™) Systems”, Accessed from: http://www.mts.com/en/products/producttype/testsystems/simulation-systems/multiaxial-simulationtables/orthogonal/index.htm

[19] Hou Y, Yang Z, Wan G. An improved dynamic voltage model of PEM fuel cell stack. International Journal of Hydrogen Energy [J]. 2010,35(20):11154 ~ 11160.

[20] Hao Dong. Study on Performance Degradation of Automotive Fuel Cell Stack under Real Road Condition[D].Shang Hai: Degree of Doctor of Tong ji University, 2017.

[21] GUO LiLun, CHEN ZhongFu, LUO JingRun. Experimental Study on the Pretension Force of Multi-bolted Structure [J]. Journal of Mechanical Strength, 2016, 38 (6): 1205 ~ 1210.

[22] Chang Xingya. Research on Loose Characteristics of Bolted Joint Used on Transmission Tower Under The Action of Wind [D]. Bao Ding: Master Degree of North China Electric Power University, 2015.

[23] YU Ze-tong, LIU Jian-hua, ZHANG Chao-qian,et al. An Experimental Study on Self-Loosening of Bolted Joints under Axial Vibration [J]. Tribology, 2015, 35 (6): 732 ~ 736.