Fatigue Analysis of Proton Exchange Membrane Fuel Cell Stacks Based on Structural Stress Distribution

C.W. Wu ¹, B. Liu ¹, M.Y. Wei ², L.F. Liu ¹

¹ State Key Laboratory of Structure Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China.
² Department of Compression Systems, Aero Engine Corporation of China Commercial Aircraft Engine Co., LTD, Shanghai 200241, China.
Email: cwwu@dlut.edu.cn

Abstract. Proton exchange membrane fuel cell (PEMFC) stack usually undergoes various vibrations during packing, transportation and serving time, in particular for those used in the automobiles and portable equipment. Based on the Miner fatigue damage theory, the fatigue lives of the fuel cell components are first assessed. Then the component fatigue life contours of the stack are obtained under four working conditions, i.e. the three single-axial (in X-, Y- and Z-axis separately) and multi-axial random vibrations. Accordingly, the component damage under various vibrations is evaluated. The stress distribution on the gasket and PEM will greatly affect their fatigue lives. Finally, we compare the fatigue lives of 4-bolt- and 6-bolt-clamping stacks under the same total clamping force, and find that increasing the bolt number could improve the bolt fatigue lives.

1. Introduction
Proton exchange membrane fuel cell (PEMFC) stacks are expected to be widely used in vehicles. In general, the requirement of stack serving life in vehicles should be more than 5000 hours [1]. However, they often encounter such problems as short life and poor durability [2]. These problems may be caused by the structural damage resulting from rigorous working conditions, especially the vibrations during the serving time [3]. Rajalakshmi et al. [4] carried out a sine sweep and random vibrating test on a 3-axis-vibrating platform and observed that the torque applied to some tightening bolt was reduced. The bolt torque release may be due to either structural failure or joint wear under vibration [5-6]. Hou et al. [7-8] finished a vibration test for PEMFC stack under strengthened road vibration and found the external leakage increased by 1.73 times. In other vibration tests, it was found that the polarization curve was changed at high current density [9-10]. Banan et al. [11] found that the increase of vibration magnitude and frequency obviously aggravates the MEA damage. To accurately study the effects of cyclic stress caused by vibration on the fatigue life, Khorasany et al. [12] conducted fatigue experiments for the PEM specimens. They used the elastic-plastic finite element method (FEM) to predict the PEM fatigue life [13]. Although their studies focus mainly on the single components, the large experimental data become the basis of our simulation. However, they left interactions between components and the structure details (such as the channels) out of consideration.
In our published work, the effects of the clamping configuration and the clamping force magnitude on vibration modes were discussed [14-15]. However, there was still no visual and quantitative analysis on the fatigue life of stack components in service. Based on the Miner fatigue damage theory [16], the fatigue life and component damage (such as bolts, gaskets and PEMs) are evaluated in the present paper.

2. Fatigue Analysis Method of PEMFC Stacks
The stacks studied here are typical bolt-clamping stacks used in vehicles [17, 18]. 10-cell-stacks (1 kW) are set up as shown in Figure 1. Along the positive Z-axis, the unit cells numbered from 1 to 10 are clamped in series along Z-axis by the endplates, bolts (M10) and nuts. The dimensions of the bipolar plate in X, Y and Z directions are 85 mm, 165 mm and 4 mm, respectively. On the bipolar plate, each parallel gas channel is 1 mm in width and 0.6 mm in depth. The cooling channel of the bipolar plate has a rectangular cross-section of 3 mm×2 mm. MEA is composed of two gas diffusion layers (GDLs) and one PEM in the middle. Here the thicknesses of GDL and PEM are 0.275 mm and 0.05 mm, respectively. The MEA sides are sealed with the gaskets. The stack rigid-body motion should be constrained. Specifically, the right endplate is fully fixed (see Figure 1), but the Z-axial translation of the left endplate is not fixed. The sizes of the endplate, collector plate and insulator plate in X- and Y-axis are 180 mm and 250 mm, and their thicknesses in Z-axis are 20 mm, 20 mm and 4 mm, respectively. The bolt positions for configurations with 4 and 6 bolts are shown in Figure 1. A torque of 12 Nm and 8 Nm are respectively applied to each bolt to provide the same total clamping force, about 22 kN [18].

GDL is made of carbon paper (TGP-H-90). This material shows isotropy and linear elasticity in XY-plane but shows nonlinear elasticity in Z-axis. All the other components are assumed to be isotropic. The operating temperature of PEM is 70 °C and relative humidness is 90% . The S-N curves of the bolt, gasket and PEM materials are straight line in log-log coordinate, i.e., the cyclic number \( N_s \) increases exponentially with the decrease of cyclic stress \( S \), as the following:

\[
S^{\alpha} N_s = C
\]

where \( \alpha \) and \( C \) are obtained by fitting material fatigue test data. For bolt, \( \alpha \) equals 2.10 and \( C \) equals \( 3.40 \times 10^9 \) [19]; for PEM, \( \alpha \) equals 7.57 and \( C \) equals \( 3.16 \times 10^9 \); for gasket, \( \alpha \) equals 2.26 and \( C \) equals \( 3.53 \times 10^5 \) [20].

In the present paper, a four hour random vibration is truncated. After periodic extension, a virtual infinite random vibration is acquired for fatigue analysis. The stacks are studied under four conditions, including the single-axial (in X-, Y- and Z-axis separately) and multi-axial random vibrations. Here
the multi-axial random vibration is the mixture of single-axial vibration in X-, Y- and Z-axis, whose weight coefficients are 1, 1 and 1, separately. The acceleration power spectral density (PSD) of random vibration in each direction is kept as the same with the PSD-curve. According to the stack vibration test criterions and corresponding literatures [21], the magnitude of acceleration usually ranges from 1 g to 20 g. Therefore we set the maximum acceleration to 20 g. The FEM model of each stack contains about 1 million elements. The fatigue life can be evaluated based on Miner fatigue damage theory.

3. Fatigue Analysis Results

3.1 Fatigue Life Contours of Bolts

The cyclic stress magnitude in stack components is one main influence factor to the fatigue lives. The endplate bending under clamping force makes the bolts bend to one side of the unit cells. In this condition, when the 4- and 6-bolt-clamping stacks are exposed to vibration, the bolts will be subjected to the coupled stress resulting from bending moment and tension. As a result, under the vibration in X- or Y-axis, the bolts have high stress near the nuts and thus have relatively short fatigue life in these regions, as shown in Figure 2. Under the vibration in Z-axis, the bolts will bear the inertia load of the whole stack in Z-axis, and thus will be subjected to a large cyclic tension stress. Due to the cyclic stress, the fatigue lives in most regions of the bolts decrease to about 1000 hours, as shown in Figures 2c and 2g. In addition, the bolts bending to one side of the unit cells will cause larger cyclic stretching stress to this side, giving rise to shorter fatigue life. As the bolt damage caused by the multi-axial vibration is the damage accumulation resulting from each single-axial vibration, fatigue lives in the most regions of the bolt are less than 1000 hours, as shown in Figures 2d and 2h.

Figure 2. Fatigue life contours of the bolts: bolts in (a-d) belong to 4-bolt-clamping stack, (e-h) belong to 6-bolt-clamping stack, applying the vibrations in (a, e) X-axis, (b, f) Y-axis, (c, g) Z-axis, and (d, h) multi-axes.
The fatigue life is usually short in the bolt regions near the nuts and endplates. When the life limit is reached, the bolt threads in those regions may give rise to fretting wear, the possible damage that may cause the torque release. These phenomena are also observed in the experiments [4]. Furthermore, the possible torque loss may also cause decreasing of the inner pressure and increasing of hydrogen leakage rate and contact resistance. In mechanical design, there are many methods to avoid torque release, for examples, spring washers applied between nuts and endplate, rough contact surfaces between nuts, washers and endplate, and etc.

Since the 6-bolt- and 4-bolt-clamping stacks share the same total clamping force, each bolt in 6-bolt-clamping stack will be subjected to a smaller tension stress. This makes their fatigue lives longer than those in 4-bolt-clamping stack under all the conditions. Especially under the vibration in Z-axis, since the bolts in 6-bolt-clamping stack are also subjected to much less inertia load due to the vibration, the minimum bolt fatigue life in 6-bolt-clamping stack is 27.4% longer than the 4-bolt-clamping stack, as shown in Figures 2c and 2g. For the same reason, when multi-axial vibration is applied to the 6-bolt-clamping stack, the minimum fatigue life is 21.3% longer than the 4-bolt-clamping stack, as shown in Figures 2d and 2h.

3.2 Fatigue Life Contours of PEMs and Gaskets

The numerical results show that some regions in the gasket and PEM will be subjected to relative larger cyclic stress, leading to the localized failure or short fatigue life. The fatigue life contours are greatly affected by the stress distribution. Based on the color histogram analysis of the fatigue life contours (in XY-plane), the ratio of the area with fatigue life less than 5000 hours to the total area can be obtained. Hereafter this “ratio” will be called “failure area ratio”. Generally, a high gasket failure area ratio will lead to a high leakage rate. A high PEM failure area ratio will result in performance degradation even a stack shutdown. As the gasket and PEM in the No.10 unit cell have relatively short fatigue life, Figures 3 and 4 demonstrate the fatigue life contours in this unit cell.

Under the vibration in X-axis, the stack will be subjected to bending. Correspondingly, warpage may occur in both left and right sides of the gasket, as shown in Figures 3a and 3e, which causes large coupled cyclic stress resulting from shearing and compression. Therefore the fatigue lives in these regions in stacks clamped with 4 and 6 bolts are both short. The fatigue lives are 3858.6 hours and 3367.7 hours, and the failure ratios are 14.0% and 15.4%, respectively. Analogously, under the vibration in Y-axis, the upwards and downwards sides of gasket have shorter fatigue lives of 4342.1 hours and 3701.6 hours, and the failure ratios are 6.7% and 11.4% respectively, as shown in Figures 3b and 3f. Thus it can be seen that under transverse (X- and Y-axis) vibration, the outside gasket region in 6-bolt stack has shorter fatigue life and larger failure ratio than that in 4-bolts region. Under vibration in Z-axis, the inertia load of unit cells in Z-axis is mostly applied to the gaskets. As a result, the gasket failure area ratio is 100% in the 4-bolt-clamping stack and 30% in the 6-bolt-clamping stack, as shown in Figures 3c and 3g. Under the clamping force and vibration in Z-axis, the outside of endplates will show bending deformation. Therefore, the outside region in the gasket bears a larger cyclic stress, whereas the internal region only needs to bear relative small stress. This would lead to a longer fatigue life in the internal gasket region. Under multi-axial vibration, the combination of the reasons mentioned above will result in the fatigue lives in the most gasket regions that are less than 2000 hours and in the outside gasket regions that are even less than 1100 hours. This may cause a severe gas leakage in the stack during the long time serving.
Figure 3 Fatigue life contours of the gaskets in the No.10 unit cell: gaskets in (a-d) belong to 4-bolt-clamping stack; (e-h) belong to 6-bolt-clamping stack, applying the vibrations in (a, e) X-axis, (b, f) Y-axis, (c, g) Z-axis, and (d, h) multi-axes.

With the service time increasing, the adding failure ratio of PEM means the shrinkage of electrochemical reaction region and the degradation of stack performance. Under vibrations in X- and Y-axis separately, the PEM in 4-bolt-clamping stack has failure area ratios of 1.1% and 0.9%, as shown in Figures 4a and 4b. Whereas, as shown in Figures 4e and 4f, the PEMs in 6-bolt-clamping stack have smaller failure area ratios, i.e. 1.0% and 0.3%. Similarly to gasket, the failure mainly occurs in the outside region of PEM. Under vibration in Z-axis, the inertia load of unit cells in Z-axis mostly applies to the gasket, which makes the PEM has a fatigue life more than 1 million hours, as shown in Figures 4c and 4g. This indicates that the single-axial vibrations may lead to very small PEM failure area ratios. Under multi-axial vibration, the PEM failure area ratios in 4-bolt- and 6-bolt-clamping stack are 13.5% and 2.6% respectively, as shown in Figures 4d and 4h. As discussed above, only small cyclic stress is generated in the PEM, resulting in the much smaller failure area ratio in PEM than that in the gasket. It is also worth mentioning that stress concentration exists in the contact areas of MEA and channel ribs, giving rise to a short fatigue life in this area. Generally speaking, most of the regions (more than 80%) of the stacks analyzed in the present paper can work for a long time. However the outside PEM regions give short fatigue lives usually less than 1000 hours.
Figure 4 Fatigue life contours of PEMs in the No.10 unit cell: PEMs in (a-d) belong to 4-bolt-clamping stack; (e-h) belong to 6-bolt-clamping stack, applying the vibrations in (a, e) X-axis, (b, f) Y-axis, (c, g) Z-axis, and (d, h) multi-axes.

4. Conclusions
(1) Under the four vibration conditions studied in the present paper, the cyclic stress distribution on the stack components will greatly affect their fatigue lives. According to the fatigue contours, the fatigue lives in the bolt regions close to nuts and the outside regions of gasket and PEM are relatively short. This may cause severe hydrogen leakage under long term vibration.
(2) Comparing the 4- and 6-bolt-clamping stacks, as the total clamping force and the inertial load along Z-axis can be shared by more bolts, the bolts in 6-bolt-clamping stack have longer fatigue lives than 4-bolt-clamping stack. The quantity and configuration of bolts will also affect the stress distribution on gasket and PEM.
(3) The structure design for the stack has a great effect on the component fatigue life. For example, increasing rigidity of endplate could decrease the magnitude of cyclic stress on the outside regions of gasket and PEM, and thus increase the fatigue lives. A different thickness design of MEA and gasket can make the stress distribution more properly and improve both the fatigue lives of gasket and PEM.

Acknowledgements
This work was supported by National Basic Research Program of China (2015CB057306), and the NSFC (11572080).

References
[1] Sharaf O Z et al 2014 An overview of fuel cell technology fundamentals and applications Renew. Sustain. Energy Rev. Vol 32 pp 810-855
[2] Wu J et al 2008 A review of PEM fuel cell durability degradation mechanisms and mitigation strategies J. Power Sources Vol 184 pp 104-119
[3] Shi W Y et al 2007 The effect of H2S and CO mixtures on PEMFC performance Int. J. Hydrogen Energy Vol 32 pp 4412-4417
[4] Rajalakshmi N et al 2009 Reliability evaluation of an open-cathode PEMFC at operating state and longtime vibration by mechanical loads Int. J. Hydrogen Energy Vol 34 pp 3833-3837

[5] Jiang Y et al 2004 An Experimental study of self-loosening of bolted joints J. Mechanical Design Vol 126 pp 925-931

[6] Basava S et al 1998 Bolted joint clamping force variation due to axial vibration J. Sound & Vibration Vol 210 pp 255-265

[7] Hou Y et al 2016 Effect of strengthened road vibration on performance degradation of PEM fuel cell stack Int. J. Hydrogen Energy Vol 41 pp 5123-5134

[8] Hou Y et al 2011 Experimental investigation of gas-tightness and electrical insulation of fuel cell stack under strengthened road vibrating conditions Int. J. Hydrogen Energy Vol 36 pp 13763-13768

[9] Betournay M C et al 2004 The effects of mine conditions on the performance of a PEM fuel cell J. Power Sources Vol 134 pp 80-87

[10] Hou Y et al 2012 An investigation of characteristic parameter variations of the polarization curve of a proton exchange membrane fuel cell stack under strengthened road vibrating conditions Int. J. Hydrogen Energy Vol 37 pp 11887-11893

[11] Banan R et al 2013 Effect of mechanical vibrations on damage propagation in polymer electrolyte membrane fuel cells Int. J. Hydrogen Energy Vol 38 pp 14764-14772

[12] Khorasany R M H et al 2015 Mechanical degradation of fuel cell membranes under fatigue fracture tests J. Power Sources Vol 274 pp 1208-1216

[13] Khorasany R M H et al 2015 Simulation of ionomer membrane fatigue under mechanical and hygrothermal loading conditions J. Power Sources Vol 279 pp 55-63

[14] Liu B et al 2016 Effect of impact acceleration on clamping force design of fuel cell stack J. Power Sources Vol 303 pp 118-125

[15] Wu C W et al 2015 Mechanical response of a large fuel cell stack to impact a numerical analysis Fuel Cells Vol 15 pp 344-351

[16] Lee Y L et al 2005 Fatigue testing and analysis: theory and practice Elsevier Butterworth-Heinemann

[17] Lin P et al 2011 Multi-objective topology optimization of end plates of proton exchange membrane fuel cell stacks J. Power Sources Vol 196 pp 1222-1228

[18] Wen C Y et al 2009 Experimental study of clamping effects on the performances of a single proton exchange membrane fuel cell and a 10-cell stack J. Power Sources Vol 192 pp 475-485

[19] Warhadpande A et al 2010 A new finite element fatigue modeling approach for life scatter in tensile steel specimens Int. J. Fatigue Vol 32 pp 685-697

[20] Tabar R J et al 1983 Soft heat and fatigue resistant elastomeric articles US4419480-A

[21] Paclisan D et al 2013 Real time modelling of the dynamic mechanical behaviour of PEMFC thanks to neural networks Eng. Appl. Artif. Intel. Vol 26 pp 706-713