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Effect of strengthened road vibration on performance degradation of PEM fuel cell stack

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ABSTRACT

The vehicular fuel cell stack is unavoidably impacted by the vibration and shock in the real-world due to the road unevenness. However, influences of vibration on fuel cell stack have yet to be investigated completely. In this paper, the performance of a fuel cell stack is experimentally studied in terms of gas-tightness, voltage degradation, AC impedance spectra, polarization curve and characteristic parameters in polarization curve through long-term strengthened road vibration tests, in order to investigate the influences of road-induced vibration on performance degradation of fuel cell stack. The vibration tests are carried out on a six-channel multi axial simulation table with the vibration excitation spectra originally derived from the strengthened road of the ground prove. During the vibration test, several kinds of performance test including gas-tightness test, AC impedance diagnosis and polarization curve test are conducted at regular intervals. After the vibration test, the gas leakage rate of anode reaches 1.73 times of the initial value. The open circuit voltage and rated voltage decreases by 0.90% and 3.58%, respectively. Meanwhile, the performance of individual cell voltage uniformity becomes worse distinctly. With the increase of vibration duration, the ohmic resistance obtained from AC impedance diagnosis ascends approximately linearly and presents a growth of 5.36% ultimately. An improved empirical fuel cell polarization curve model is adopted to fit the current–voltage data and estimate the characteristic parameters which decide the shape of polarization curve. It is noted that the limiting current density declines distinctly and the mass transfer loss increases mainly at the range of high current densities. The results indicate that the long-term strengthened road vibration condition exerts a significant influence on the durability of fuel cell stack.

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Introduction

Due to the growing concerns on the depletion of petroleum and climate change, fuel cell (FC) technologies have received much attention and develop rapidly in recent years. Proton exchange membrane fuel cell (PEMFC), which converts the chemical energy stored in hydrogen directly and efficiently to electrical energy with water as the only byproduct [1], is widely regarded as the most competitive power source for future zero emission vehicles with its remarkable features such as high efficiency, low operating temperature, fast start-up and shut-down and low noise [2].

The commercial success of PEMFC in transportation applications depends highly on the durability. Consequently, lots of studies on durability have been carried out to prolong the lifetime of PEMFC in recent decades. However, currently challenges still remain to fulfill the US Department of Energy (DOE) target of 5000 operating hours for passenger vehicles [3]. In transportation applications, the PEMFC is subjected to harsh operational conditions, such as hydrogen and air impurities [4], cold start [5,6], dynamic cyclic loads [7,8], temperature and humidity cycles [9,10] road-induced vibration and shock [11], etc. Among the above conditions, the road-induced mechanical vibration has not been widely investigated at present. Passenger vehicles generally experience vibration due to road unevenness and oscillations of the axles and wheels with the suspension system [11]. As a key component of FC vehicle, the vehicular FC stack is generally exposed to road-induced vibration and shock, which are absolutely unavoidable and could exert complicated effects on the stack. Nevertheless, only a few papers have been published concerning the performance degradation of FC stack under vibrating condition.

Investigation of a 500W PEMFC stack through a vibration and shock test by subjecting the device to random and swept-sine excitations on a vibrating platform was carried out by Rajalakshmi et al. [12]. During the vibration test, the stack was shaken from 30 Hz to 150 Hz at a constant acceleration of 3 g for about 90 min in three axes respectively. The shock test was conducted at 30 g for a pulse width of 15 ms with 10 pulses in both horizontal and vertical axes. After the test, no significant damage effects were observed. However, there was a minor compression force release at the bolts after each vibration or shock test. Rouss et al. [13,14] conducted vibration test of a FC stack for airplane applications, where the vibration frequency ranged from 6 Hz to 2000 Hz, the amplitude of acceleration ranged from 1 g to 20 g. The test results showed that the variation of the leakage rate between the beginning and the end of the test series was not significant and thus, no problem of membrane cracks or other malfunctions in the stack were observed. Betournay et al. [15] experimentally investigated the effects of underground mining conditions, shock, and vibration on a 35 W FC stack. After 49 h shock and vibration tests, a slight variation of the polarization curves at high current density was observed. In another paper, Diloyan et al. [16] studied the effect of vibration on Pt particle agglomerations in the catalyst layer. They showed that the average diameter of Pt agglomerates under vibration was 10% smaller than those that were not exposed to vibration. The damage propagation in the membrane electrode assembly (MEA) under vibration condition was investigated by Banan et al. [17]. Non-linear relationships were found between the damage propagation and the parameters such as amplitude and frequency of vibration, initial delaminating length. And then Banan et al. [18] investigated the combined effects of hygrothermal cycle amplitude and amplitude and frequency of external vibrations on damage propagation through finite element method. They found that the simultaneous presence of hygrothermal cycles and vibrations severely intensified damage propagation within the expected FC lifetime. Recently, Wu et al. [19] found that the individual cells may slip relative to one another when the FC stack was subjected to large impact acceleration in the direction parallel with the cell. The relative slippage was affected by the stack clamping force, impact acceleration and the friction coefficient between cells. This relative slippage appeared under mechanical vibration and impact may induce the performance variations of FC stack. While the research works mentioned above have provided valuable and significant insight into the effects of mechanical vibration on FC, further studies are needed to investigate and improve the durability of FC stack under the road-induced vibration condition.

In the earlier investigations of the author [20–22], a long-term strengthened road vibration test was conducted to analyze the performance variations of a 45 kW FC stack. The safety performances degraded distinctly during the test. Besides, a fluctuating variation of the polarization curves was observed. It is particularly worth noting that the steady-state efficiency of the stack declines evidently. Hence, more experimental studies are required to verify and investigate the performance variations of the vehicular FC stack under road-induced vibrating condition. On the basis of the previous researches, a series of experiments were conducted on a 9 kW FC stack, which are assembled with 90 cells of 250 cm^2 effective area in series, to investigate the variations of performance under strengthened road vibration. Compared with the earlier investigations, there were some improvements in this work, as follows:

a) Twelve performance tests were conducted during 250 h vibration test. The time intervals between performance tests were much shorter and more disciplined than before. Hence, it is helpful to particularly observe the performance variations under the vibration condition.
b) In the earlier study, only the performance data of stack was sampled. In this work, both the stack and individual cells were monitored during performance test. The parameters including rated voltage, voltage drop rate and coefficient of variation are adopted to evaluate the operation uniformity of the stack. Moreover, the relevant reasons for non-uniform degradation are discussed.
c) During polarization curve test, the maximum test current density was much higher and the test points of current density were much more. A higher test current density is beneficial to observe the mass transfer phenomenon and more test points in the region of activation polarization are conducive to deduce the activation kinetics parameters. As a consequence, more steady-state performance information over the entire operational range was obtained.