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Vibration mode analysis of the proton exchange membrane fuel cell stack

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HIGHLIGHTS

- The mode analysis of stack based on finite element method is carried out.
- The local vibration modes are distinguished from global vibration modes.
- Effects of clamping configuration and clamping force on vibration response are discussed.

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ABSTRACT

Proton exchange membrane fuel cell (PEMFC) stacks usually undergo vibration during packing, transportation, and serving time, in particular for those used in the automobiles or portable equipment. To study the stack vibration response, based on finite element method (FEM), a mode analysis is carried out in the present paper. Using this method, we can distinguish the local vibration from the stack global modes, predict the vibration responses, such as deformed shape and direction, and discuss the effects of the clamping configuration and the clamping force magnitude on vibration modes. It is found that when the total clamping force remains the same, increasing the bolt number can strengthen the stack resistance to vibration in the clamping direction, but cannot obviously strengthen stack resistance to vibration in the translations perpendicular to clamping direction and the three axis rotations. Increasing the total clamping force can increase both of the stack global mode and the bolt local mode frequencies, but will decrease the gasket local mode frequency.

1. Introduction

Proton exchange membrane fuel cell (PEMFC) stack, as one of the most widely used fuel cells, has received much attention in the field of new power resources [1,2]. The PEMFC stacks used in automobiles and portable equipment are inevitable to encounter various vibrations [3], which probably result in structural damage of the fuel cell components [4]. Some structural damages have been detected in experiments, such as crack and delamination in membrane electrode assembly (MEA), fiber crack in gas diffusion layer (GDL) [5–7]. Those structural damages will lead to degradation of fuel cell performance [8]. For instance, Hou et al. [9–11] found in a strengthened road vibration test that the damage of gaskets made the hydrogen leakage rate increased by 50%.

As the global resonance will cause terrible damage to a PEMFC stack, Rouss et al. [12] have made a vibration test for a stack on a 3-axes vibration platform to obtain the resonant frequency and the positions with a considerable mechanical response. If the stack is under a long-term vibration load, the local vibration response of some components (such as gaskets) might also lead to local structural damage. Rouss et al. [13] established a neural network model of PEMFC stack. It can give mechanical response of specific observation points in the stack and detected local damage under multi-direction excitation. Apart from this, vibration mode analysis method can decouple the structure vibration problem. Since the local vibration response is often unapparent, it is difficult to identify merely based on experimental mode analysis. Using finite element method (FEM) in mode analysis, we can obtain the frequency and deformation for every vibration mode of the stack. To date, Ozgur et al. [14] carried out mode analysis on a stack with FEM method. They showed a good agreement between the theoretical analysis

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and the experiment (frequency error less than 8.3%). Ahmed et al. [15] simplified PEMFC as a multilayered composite structure and analyzed the response of a single cell to vibration. The effects of the component thickness, elastic modulus and density on vibration modes were discussed. Deshpande et al. [16] analyzed the modes of a PEMFC stack, and found that the hydrogen leakage rate increases linearly with vibration acceleration. Hong et al. [17] found that even though a small change in the stack structure can result in a significant variation in local vibration modes. Therefore, to accurately simulate and distinguish the global and local vibration modes, even small structures (such as cooling channels) of the stack should also be considered in detail. However, this will need a large computational resource. Therefore, up to date, no related reports are found to discuss the global and local vibration modes separately. Since a large PEMFC stack is usually clamped together using either clamping bolts [3,12] or steel belts [18–20], the clamping configuration and clamping force magnitude will significantly affect the PEMFC stack vibration response. However, little discussion about their effects can now be found. In the present paper, we will study the vibration modes of a PEMFC stack under bolt-clamping arrangements.

We first set-up FEM analysis models of 10-cell stacks considering the non-linear mechanical properties of components (such as gas diffusion layers). Then, comparing the effective mass of each mode, the main vibration modes can be identified. Accordingly, the vibration response of the stack, *i.e.* the deformed shape and direction, can be predicted. The effects of clamping configuration and clamping force magnitude on global and local vibration response are also discussed.

2. Mode analysis of the PEMFC stacks

2.1. Theory of mode analysis

The free vibration equation of the structure can be expressed as:

$$M\ddot{u} + Ku = 0 \tag{1}$$

where K represents for stiffness matrix and M is mass matrix. The general solution of u is a linear combination of each mode [21]:

$$u = \sum_n \varphi_n q_n e^{i\omega_n t} \tag{2}$$

where φ_n and ω_n are the nth vibration mode and its frequency, respectively. The constant, q_n, can be evaluated from the initial conditions. Here we define the generalized displacement vector x and mode matrix Φ as the following:

$$x = \left(q_1 e^{i\omega_1 t} q_2 e^{i\omega_2 t} \ldots q_n e^{i\omega_n t}\right)^T \tag{3}$$

$$\Phi = (\varphi_1 \varphi_2 \ldots \varphi_n) \tag{4}$$

It should be noticed that PEMFC stack is usually fixed at the automobile and other portable equipment with a substructure. The vibration load is transmitted to PEMFC stack through the substructure motion. In mode analysis, this substructure motion is defined as the base motion excitation, u_b, and the vibration equation can be expressed as:

$$M\ddot{u} + Ku = -M\sum_{j=1}^{6} T_j(\ddot{u}_b)_j \tag{5}$$

where the base motion excitation is expressed by the global inertial load in the X, Y or Z translation ($j = 1, 2, 3$) or rotation ($j = 4, 5, 6$). T_j is the inertia indicator vector (equal to either 0 or 1), *i.e.* the magnitude of the rigid motion in either j translation or rotation.

The displacement vector u in Eq. (5) can be transformed to generalized displacement x_n by premultiplying the modal matrix Φ. Then the PEMFC vibration equation can be expressed as:

$$\ddot{x}_n + \frac{k_n}{m_n}x_n = -\sum_{j=1}^{6}(\Gamma_n)_j(\ddot{u}_b)_j \tag{6}$$

where k_n and m_n stand for the generalized stiffness and generalized mass of the nth mode, respectively:

$$k_n = \varphi_n^T K \varphi_n \tag{7}$$

$$m_n = \varphi_n^T M \varphi_n \tag{8}$$

Then, the modal participation factor, Γ_n, is defined as the following:

$$(\Gamma_n)_j = \frac{1}{m_n}\varphi_n^T M T_j \tag{9}$$

and the effective mass can be defined as:

$$\left(m_n^{eff}\right)_j = m_n(\Gamma_n)_j^2 \tag{10}$$

Comparing each effective mass, we can distinguish the main vibration modes. In addition, comparing the effective mass in different directions for a given mode, the main vibration direction of this mode can be obtained [22].

2.2. FEM model of PEMFC stacks

Fig. 1 shows a 10-cell PEMFC stack (1 kW). The dimensions of the stack in X, Y and Z directions are 180 mm × 250 mm × 175 mm. The original point of the rectangular coordinate is placed on the stack gravity center. The 10 unit cells are placed in series and clamped by the endplates, bolts and nuts. Direction of the applied clamping force is along Z-axis. The detailed geometric dimensions are referenced to the previous work [23,24]: dimensions of the bipolar plate in X, Y, and Z directions are 85 mm × 165 mm × 4 mm; each gas channel is 1 mm in width and 0.6 mm in depth. Parallel straight cooling channels are placed in the middle of every bipolar plate, and each cooling channel has a rectangular cross-section of 3 mm × 2 mm. MEA is a sandwich structure composed of two GDLs and one proton exchange membrane (PEM) in the middle. The thickness of PEM and GDL are 0.05 and 0.275 mm, respectively. Both sides of MEA were sealed with the gaskets. The rigid-body motion of the right end plate shown in Fig. 1 is fully constrained, but the rotation of the left one is constrained by the guide rails [25]. The dimensions of endplate, insulator plate, collector in X and Y directions are 180 mm × 250 mm, and their thickness in Z direction are 20 mm, 20 mm and 4 mm respectively.

GDL is made of carbon paper (TGP-H-90), which can be assumed to be quasi-isotropic material [27]. The material properties of GDL are listed in Table 1. GDL shows isotropy linear elasticity in XY-plane and nonlinear elasticity in Z direction. The shear modulus in XY-plane can be calculated from the following equation:

Fig. 2 shows the position of the clamping bolts for configurations with 4 and 6 bolts [23,24]. For a 6-bolt-stack, under 16 N m clamping torque for each bolt, some of the stack components (such as PEM) reach the strength limit. In the present paper 16 N m is set to be the upper limit of the clamping torques. The stacks with the