Construction and Application of Prediction Spectrum between PEMFC’s Performances and Ship Vibration

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Abstract: In order to analyze and evaluate the influence of ship vibration on the performance of proton exchange membrane fuel cell (PEMFC), firstly, the frequency domain and amplitude distribution characteristics of ship vibration are studied. Based on the general PEMFC simulation mathematical model, a boundary condition, loading method based on sliding grid technology (ZM-UDF) is proposed to establish the technical route of numerical simulation of PEMFC influence relationship on ship vibration performance. Secondly, in the full solution domain of ship vibration, a numerical simulation scheme is designed to study the influence of ship vibration direction, frequency and amplitude on the performance of proton exchange membrane fuel cell (PEMFC). Through simulation calculation, the performance database of ship vibration-proton exchange membrane fuel cell is constructed. Furthermore, the linear programming model of simulation data is established by using the difference-piecewise fitting method, and a prediction map construction method of ship vibration proton exchange membrane fuel cell performance characterization based on numerical simulation data is proposed. The performance prediction map of ship vibration proton exchange membrane fuel cell is drawn and verified by simulation.

1. Introduction

The issue of carbon emission from ships has become one of the focuses of international attention. In April 2018, IMO formulated the preliminary strategy of industry gas emission reduction, and proposed that by 2050, the greenhouse gas emission reduction of shipping industry will be reduced by 50% compared with that in 2008[1]. Ship cleaning technology is imperative. In recent years, fuel cell (PEMFC) has attracted the attention of many experts. It is believed that this technology will provide a systematic technical solution for the vibration, noise, gas pollution and other problems that cannot be effectively solved in the shipbuilding industry. At present, many countries and enterprises have started the fuel cell ship program, such as abb of Sweden, Havyard group of Norway. Therefore, it is of great significance to further improve the performance of fuel cells in ship vibration environment.

In previous studies, El EMAM et al. conducted three-phase vibration experiments in 2015[2], which showed that the PEMFC performance would be improved when the PEMFC stack was subjected to 1.33hz, 2Hz and 3Hz vibration loads. In 2016, Wang x et al. reached the same conclusion as El EMAM et al[3]. In the second year, Sellman J T et al. combined with previous theoretical and experimental studies, designed an experimental method of bottom injection of droplets, which better simulated the formation process of PEMFC droplets.[4] Hou et al. carried out a series of vibration tests from 2011 to 2016 to
study the air tightness, electrical insulation and polarization of PEMFC stack under road vibration\cite{5-8}. The test results show that the hydrogen leakage rate of fuel cell stack increases by 1.5 times under vibration condition; The insulation resistance of the battery pack will drop to 17% of the original; Both ohmic polarization and active polarization of the cell will be affected. The team finally came to the conclusion that vibration has a significant impact on PEMFC stack durability, which cannot be ignored in the research. In 2019, S. Ahn et al. measured the vibration modes of PEMFC through experiments, and proposed a measurement method to determine the effective dynamic characteristics of laminated structures\cite{9}. In the next year, D. Jiao et al. used the stochastic method to reconstruct the GDL layer with different porosity, and gave the mechanism of the effect of water transport process on the performance of PEMFC under vibration condition through simulation calculation\cite{10}.

To sum up, the current research focus on the mechanical behavior of PEMFC stacks after vibration, and the transmission characteristics of liquid water in the channel. There are few studies on the influence of ship vibration on PEMFC output performance. Based on the mainstream mathematical model and numerical simulation method of PEMFC, this paper proposes the loading method of ship vibration load, studies the relationship between the performance of single channel PEMFC and ship vibration, and constructs the map of ship vibration load output performance of PEMFC by using the spectrum method. The spectrum can quickly predict the quantitative changes of PEMFC performance under ship vibration environment, and provide the necessary basis for the dynamic management of marine PEMFCs.

2. Basic Principle of PEMFC

The PEMFC domain consists of nine parts: anode and cathode collectors, anode GDL, cathode GDL, anode and cathode channels, anode and cathode catalyst layers (CL), membrane; The catalytic layer is the place for electrochemical reaction; The gas diffusion layer mainly provides channels for reaction gas diffusion and liquid water removal. In general, membrane electrode assembly (MEA) is composed of membrane, catalytic layer and GDL; Collector plate, has channels on both sides. It mainly plays the role of evenly distributing gas, connecting single cell in series, collecting conductive current, supporting membrane electrode and bringing out water generated by electrochemical reaction. Its schematic diagram is shown in Figure 1.

The working principle of PEMFC is the reverse process of electrolyzing water. Hydrogen and oxygen enter the diffusion layer through the bipolar plate channel of anode and cathode respectively, and then reach the catalytic layer through the gas diffusion layer. Electrochemical reaction takes place in the
catalytic layer, in which H2 of anode is decomposed into protons (H+) and negatively charged electrons. The H+ of the anode reaches the cathode through the proton exchange membrane, and the electrons cannot pass through the membrane material, but reach the catalytic layer of the cathode through the external circuit. At the same time, in the cathode catalytic layer, chemical reaction occurs with H+ and O2 which reaches the cathode catalytic layer through the cathode channel and diffusion layer to generate water. Therefore, the total reaction of PEMFC can be expressed as equation (1).

\[ H_2 + \frac{1}{2} O_2 \rightarrow H_2O + \text{power + heat} \]  

(1)

3. Models

3.1 Geometric model

The single channel model has the characteristics of simple design and less calculation, so this study selected this model as the research object. Basic parameters of the model: the peripheral dimension is 50 mm × 1.1 mm × 435 mm, in which the length of the runner is 50 mm, and the width and depth of the runner are 0.5 mm × 0.4 mm, 0.5 mm, 0.2 mm, 0.01 mm, and 0.015 mm respectively. The grid number of the final calculation model is 130000, as shown in Figure 2.

![Figure 2](A) schematic diagram of geometric model (B) schematic diagram of mesh generation

3.2 Theoretical models

The PEMFC model is based on the basic assumption of fluid mechanics in macro scale, which is controlled by mass conservation, momentum conservation equation and so on. The fluid mass conservation equation is as follows:

\[ \frac{\partial (\rho g)}{\partial t} + \nabla \cdot (\rho g u) = S_m \]  

(2)

In Equation 2, \( \rho g \) is the gas density, \( u \) is the gas propagation velocity, \( S_m \) is the mass source term, and \( \varepsilon \) is the porosity. \( \varepsilon \) is equal to 1 in the flow channel and less than 1 in the porous medium layer.

The momentum conservation equation is expressed by Equation 3.
In Equation 3, the left side of the equation is the non-steady-state term and the convection term, and the right side of the equation is the diffusion term, where $p$ is the pressure and $\mu$ is the viscosity. $s$ represents the momentum source term.

Assuming that the ship vibration is simple harmonic vibration, combined with the relevant research results of Wang et al., the vertical vibration of PEMFC has the greatest impact on its performance. In this paper, only the vertical harmonic vibration of the ship is considered, and the vibration load model is shown in equation (4).

$$F = A_y \sin(2\pi f_y t)$$

In equation (4), $A$ is the amplitude, $f$ is the frequency, and $t$ is the time. Further, the vibration load model is loaded into the momentum conservation equation, that is, the momentum equation considering the influence of vertical vibration of the ship is obtained, as shown in equation (5).

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\rho \mu \nabla \mathbf{u}) - \rho A \pi^2 f^2 \sin(2\pi ft)$$

4. Simulation and Analysis

Taking the ship vertical harmonic vibration with frequency of 2Hz and amplitude of 0.2mm as the load, the working environment of PEMFC is set at 343K, the humidity of anode gas is 100%, and the cathode is not humidified; The operating pressure is 0.2MPa, the inlet mass flow of air is $3.383253 \times 10^{-8}$kg/s and the inlet mass flow of hydrogen $7.339254 \times 10^{-7}$kg/s. The mass fraction of hydrogen is 0.38, the rest is water vapor, and the mass fraction of oxygen is 0.233. After sorting out the calculation results, it is found that in the GDL layer, the hydrogen molar mass changes periodically with time, and its change law is related to the vibration intensity. The greater the vibration intensity is, the greater the fuel consumption is, and the obvious starvation area appears, as shown in Figure 3.

![Fig. 3 Variation of hydrogen molar concentration on the middle surface of anode GDL layer(0.2mm-2hz)](image-url)
According to the results shown in Figure 3, the distribution of hydrogen concentration in GDL layer will change with the change of vibration load. In view of this phenomenon, a further quantitative analysis is carried out. Taking the average hydrogen molar concentration as the assessment quantity, the dynamic change curve is formed, namely figure 4. In Figure 4, it can be seen that the voltage changes periodically with time, while the output voltage of anode GDL layer changes periodically with time, The average concentration of hydrogen in CL layer and anode channel is consistent with the change of voltage, which reaches 0.06kmol/m$^3$ at the lowest vibration load intensity, and less than 0.04kmol/m$^3$ at the highest vibration intensity. This shows that the average hydrogen concentration distribution is positively correlated with the output voltage, and the periodic vibration load will affect the hydrogen concentration distribution. When the vibration load is high, the hydrogen consumption increases, the average hydrogen concentration in each area of the anode decreases, and the voltage decreases significantly. When the vibration load is weak, the hydrogen consumption is weak and the output voltage rises, but the voltage will not return to the steady state due to the consumption.

Figure 4. Influence of vibration load change on average hydrogen molar concentration of PEMFC anode(0.2mm-2hz)

Through simulation calculation, it is found that if the vibration load is too large, PEMFC will be unable to continue the reaction due to the excessive consumption of hydrogen fuel, and the voltage drops to 0. At this time, the starvation phenomenon occurs in PEMFC, and PEMFC cannot output voltage.

5. Prediction Spectrum
Through 18 groups of simulation examples, the PEMFC performance prediction map with the simple harmonic frequency of 2hz-20hz and amplitude of 0.2mm-0.8mm is obtained, as shown in Figure 5. In Fig. 5, when the amplitude is constant, the voltage is distributed with frequency as a quadratic function. When the amplitude is constant, the output voltage decreases with the frequency rise, while when the frequency is constant, the output voltage decreases with the amplitude increase, which is consistent with the results obtained above.
6. Conclusions
The dynamic response relationship between ship harmonic vibration and PEMFC performance is analyzed and discussed by simulation method. The conclusions are as follows.

1. The results show that the internal mass transfer process of PEMFC is obviously affected by ship vibration, and the influence degree increases with the increase of vibration intensity.
2. The results show that the output voltage of PEMFC is truncated and continuous. When the output voltage is continuous, the output voltage of PEMFC is quadratic function with frequency. When the output voltage is truncated, the cut-off time of PEMFC is exponential function with frequency.
3. Ship vibration PEMFC performance prediction atlas can quickly predict the output voltage of PEMFC corresponding to different ship vibration, and it is highly consistent with the simulation results.

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