2022-01-0695 Published 29 Mar 2022

# Dynamic Modeling of Fuel Cell Air Management System and Influence Analysis of Motor Torque Ripple

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***Citation:*** Chen, S., Zuo, S., Wu, Z., and Liu, C., "Dynamic Modeling of Fuel Cell Air Management System and Influence Analysis of Motor Torque Ripple," SAE Technical Paper 2022-01-0695, 2022, doi:10.4271/2022-01-0695.

Received: 16 Jan 2022 Revised: 16 Jan 2022 Accepted: 09 Jan 2022

## Abstract

The performance of the air compressor influences that of the fuel cell system significantly. Therefore, it is urgent to develop a high-performance air compressor for fuel cell vehicles. In this paper, an analytical model of centrifugal compressor performance is established, which can predict the performance of centrifugal compressors under various speeds precisely. Then, the dynamic model of the electric-driven centrifugal compressor system is presented considering rotor dynamics and the dynamic characteristics of the motor. The torque ripple caused by the non-sinusoidal distribution of the permanent magnet field is considered. Based on experiment results, the output performance of the fuel cell stack is modeled. Finally, the influence of motor torque ripple on the performance of centrifugal compressor and fuel cell system is analyzed through simulations. The results show that torque ripple causes lower speed oscillation under high speeds so that it has little effect on the output performance of the centrifugal compressor. Therefore, in the case of matching the operating conditions of the centrifugal compressor and the fuel cell stack, the low-speed operation time of the centrifugal compressor should be reduced. For the electric-driven centrifugal compressors, whose long-running operations are medium-high speed conditions, torque ripple is not the main consideration in the motor selection or design, and the switched reluctance motor is a good choice. Moreover, contrary to intuition, the motor torque ripple can improve the stability of the compression system. This study can guide the design of high-performance centrifugal compressors for fuel cell vehicles.

## Introduction

Aiming at energy conservation and environmental protection, fuel cell systems have become one of the most promising power sources on vehicles. Fuel cells have the advantage of high efficiency, zero-emission, and low noise. These features are expected to accelerate the fuel cell system's market entry [1-3]. With the development of fuel cell vehicles, cost control is attracting more and more attention. In 2018, the most sensitive factor influencing the system cost shifted to the air-feeding subsystem, e.g., compressor, air stoichiometry, etc. [4, 5]. In 2019, the Ministry of Science and Technology of China (MOST, China) launched the 2019 key project of renewable energy and hydrogen energy technology, of which, the compressor development with 0.125 kg/s, pressure ratio 2.5, 16 kW, and 15 kg is one of the subprojects. Obviously, the government hopes to tackle the problem of low power density, flow rate, and PR in the field of vehicle fuel cells. Therefore, it is urgent to develop an air compressor with high performance for fuel cell systems.

The centrifugal compressor is widely used for the air auxiliary system of fuel cell systems, due to its high-pressure ratio and low noise [6]. Compared to the turbocharger, the electric centrifugal compressor has a simple structure and fast control response. To analyze the dynamic characteristics of the centrifugal compressors and design the stability control, it is necessary to establish the dynamic model for the electric centrifugal compressor system [7]. Moore and Greitzer proposed a dynamic model for predicting the dynamic characteristics of axial compressors, i.e. the classic M-G model [8, 9]. Hasen et al. found that the M-G model is also suitable for the centrifugal compressor systems [10]. In the M-G model, the model for predicting the performance of air compressors is challenging.

Many researchers obtained the compressor performance model through the polynomial fitting [11-14]. This modeling method is accurate and can be used for the model-based control design. However, it is difficult for the model to reflect the influence of speed change. Zhao et al. modeled the compressor using the neural network method, which can reflect the influence of speed change, but the neural network model is a black-box approach and cannot be used to design the model-based controller [15, 16]. Moreover, this method requires a lot of experimental data. So the analytical model is better, which is the theoretical derivation based on thermodynamics and velocity triangle. Jiang et al. presented a dynamic model of a centrifugal compressor capable of system simulation in the virtual test bed computational environment

**FIGURE 11** The influence of the torque ripple on the stability of the compression system.

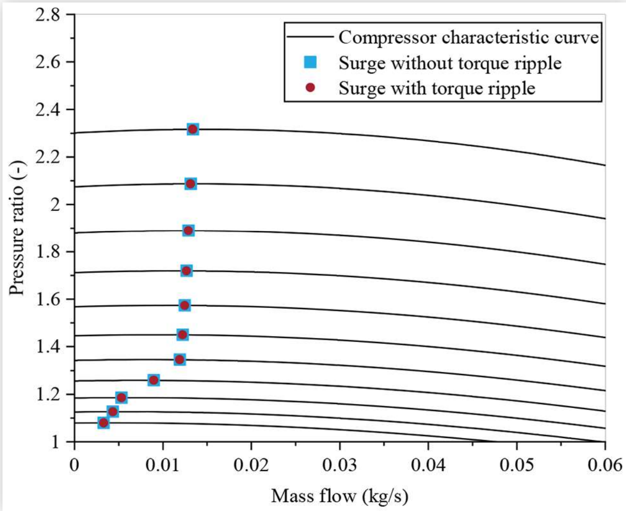


**FIGURE 12** The influence of the torque ripple on the surge margin of the centrifugal compressor.

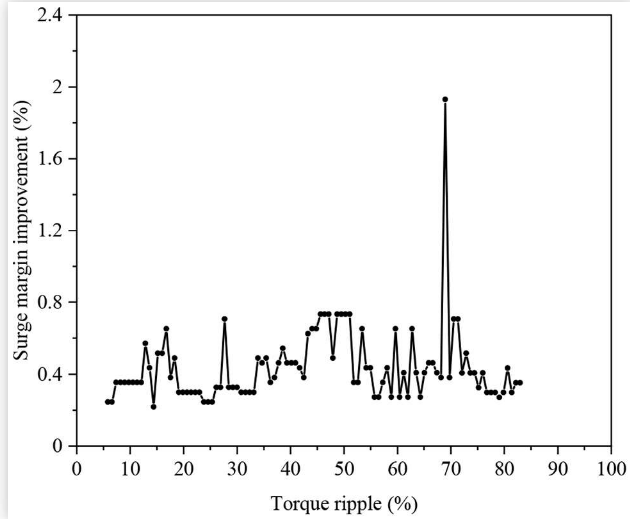


**TABLE 1** Surge margin of the centrifugal compressor.

| Compressor speed (RPM) | Surge margin without torque ripple (kg/s) | Surge margin with torque ripple (kg/s) |
|---|---|---|
| 102160 | 0.01341 | 0.01338 |
| 94863 | 0.01316 | 0.01313 |
| 87568 | 0.01292 | 0.01289 |
| 80273 | 0.01269 | 0.01268 |
| 72977 | 0.01247 | 0.01247 |
| 65681 | 0.01225 | 0.01224 |
| 58386 | 0.01192 | 0.01191 |
| 51106 | 0.00897 | 0.00897 |
| 43824 | 0.00534 | 0.00534 |
| 36524 | 0.00435 | 0.00435 |
| 29223 | 0.00330 | 0.00330 |

# Summary/Conclusions

The centrifugal compressor is driven by the electric motor, so the performance the centrifugal compressor and the fuel cell system is influenced by the motor significantly. It is important to develop a dynamic model of the electric centrifugal compressor system. In this paper, the dynamic model of the electric centrifugal compressor is proposed, and the torque ripple caused by the non-sinusoidal distribution of the permanent magnet field is considered to modify the ideal motor model. Then, the model of the fuel cell performance is established based on the experimental data. Finally, the influence of the motor torque ripple on the performance of the centrifugal compressor and fuel cell is quantitatively analyzed. The main conclusions drawn from this study are summarized as follows:

a) The dynamic model of the fuel cell air management system considering the dynamic characteristics of the motor can reflect the influence of motor torque ripple on the performance of the centrifugal compressor. Based on the dynamic model, a quantitative analysis can be conducted.

b) The torque ripple has little influence on the speed of the centrifugal compressor at high speeds. For electric centrifugal compressors which usually operate at high speeds, the torque ripple of the motor is not a key consideration of the motor design. The switched reluctance motor can be selected as the driven motor of the high-speed centrifugal compressor, because the negative influence of the large torque ripple can be mitigated in this case, which is the pain spot of the switched reluctance motor.

c) When the compressor operates at high speeds, the effect of the torque ripple on the performance of the compressor and fuel cell can be mitigated. To reduce the adverse effect of torque ripple, it is necessary to reduce the time of the compressor operating at low speeds when matching the compressor and fuel cell stack operating conditions.

d) Contrary to intuition, the motor torque ripple can improve the stability of the compression system. The improvement can even reach about 2% at high speeds. However, the improvement is not obvious when the centrifugal compressor operates at low speeds.

e) In the dynamic model, the dynamic model of the permanent magnet synchronous motor can be replaced by other motors to guide the motor selection for electric centrifugal compressors. Moreover, this model can not only be used to analyze the influence of the motor torque ripple on the performance of the centrifugal compressor and fuel cell but also design the active surge control strategy for the centrifugal compressor.

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## Acknowledgments

The authors gratefully acknowledge the financial support by National Natural Science Foundation of China (51875410).

## Definitions/Abbreviations

**M-G model** - Moore-Greitzer model

**SSO** - Specific speed oscillation