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Aerodynamic Performance Modeling of the Centrifugal Compressor and Stability Analysis of the Compression System for Fuel Cell Vehicles

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Abstract

The centrifugal compressor is one of the most commonly used air compressors for fuel cell air supply systems, and it has the small volume, high pressure ratio and low noise. However, surge in a centrifugal compressor severely limits its stable flow range. In this paper, a mathematical model of the compressor aerodynamic performance based on the energy transfer method was established, some parameters of model were identified by experimental data, and the model was validated through experiments. Then the dynamic model of the compression system was derived based on the compressor model and the Moore-Greitzer model. The stability analysis of the compression system was conducted, and it was strictly proved that when the compression system is unstable, there is the limit cycle in this nonlinear system, namely the surge cycle. Furthermore, the simulation of the compression system was conducted and the instability condition of the compression system was presented. The results show that at almost all constant speeds, the compression system instability occurs as the opening of the throttle valve decrease to a specific value, and at some opening of the throttle valve, the compression system instability occurs as speed decrease to a specific value. At last, the effects of structural parameters of the compression system on surge characteristics were analyzed. This research can guide the operating condition match of compressors and the active surge control design of the compression system for fuel cell vehicles.

Introduction

The proton exchange membrane fuel cell is a competitive clean power source due to its high efficiency, high energy density and zero emission [1, 2]. The centrifugal compressor is one of the most potential air compressors for the air supply system of fuel cells [3]. In order to improve the efficiency of fuel cell systems, centrifugal compressors tend to operate near the surge line [4]. Under rapidly changing operating conditions, surge might occur in the compression system, which is likely to damage the proton-exchange membrane and cause blade fatigue [5, 6]. Therefore, studying the stability of the compression system and surge characteristics is very significant for the development of fuel cell systems.

Surge is a global flow instability occurring in centrifugal compressors at low mass-flow rate operation. There are many kinds of research with respect to the flow instability inception by experiments and computational fluid dynamics. At surge, global flow oscillation in the form of a limit cycle at a distinct frequency occurs [7]. Stein developed a new numerical method to simulate the transient viscous fluid flow in turbo-machinery parts and this method was used to investigate the phenomena that cause flow instabilities in a centrifugal compressor [8]. Bulot et al. investigated the flow inside the impeller when the compressor operated near the surge condition [9]. In a high-speed small-scale centrifugal compressor with the vaneless diffuser, the impeller leading-edge stall is a necessary part of the mild surge, while the diffuser rotating stall incepts the deep surge [10]. These researches deepen the understanding of the flow instability in compressors.

Model-based approaches are important for studying the complex system [11]. Greitzer et al. proposed a famous axial compressor model (MG model) to reflect the dynamics of the mass flow, pressure and compressor speed [12, 13]. This model is usually used to design active surge control. Hansen found that this model is also effective for centrifugal compressors [14]. In the MG model, the compressor aerodynamic performance model is very crucial. Zhao et al. modeled the compressor using the neural network method [15]. But the neural network model cannot be used to optimize the compressor parameter and design the model-based controller. After that, they proposed a semi-physical model of the compressor performance and designed a feedforward controller for the compressor [16]. Many kinds of researches with respect to surge simulation and surge control design using the MG model were conducted. However, there is no strict proof of the existence of the limit cycle in the MG model.

is changed. In order to compare the surge characteristics with different plenum volumes in the frequency domain, time domain signals of mass flow and pressure were transformed by fast Fourier transform (FFT). The peak frequency represents the frequency of surge. As is shown in Figure 11, as the volume of the plenum increases, there is no significant change in the oscillation amplitude of mass flow, and the oscillation frequency of mass flow decreases. As the volume of the plenum increases, the amplitude of pressure drops sharply, and the frequency of pressure pulsation decreases.

Second, the effects of L_c on surge characteristics is studied. The volume of the plenum is $0.02m^3$, and the length of the pipe is changed. In order to compare the surge characteristics with different plenum volumes in the frequency domain, time domain signals of mass flow and pressure were transformed by FFT. The peak frequency represents the frequency of surge. As is shown in Figure 12, as the length of the pipe increases, there is no significant change in the oscillation amplitude of mass flow, and the oscillation frequency of mass flow decreases slightly. As the length of the pipe increases, the amplitude of pressure increases, and the frequency of pressure pulsation decreases slightly.

Summary/Conclusions

In this paper, a mathematical model of the compressor aerodynamic performance was established. The stability analysis of the compression system based on MG model was carried out and it was strictly proved that when the compression system is unstable, the limit cycle arises in this nonlinear system. Furthermore, the simulation of the compression system was conducted and the instability condition of the compression system was presented. The effects of structural parameters on surge characteristics were studied.

a. The mathematical model of the compressor characteristic curve has a good agreement with the experiments. It can predict the aerodynamic performance at the other speed, which was not measured, and it is the foundation of the compression system model.
b. When the compression system becomes unstable, the limit cycle arises. Surge occurs in the compression system at two kinds of changing operating conditions. One is that at almost all constant compressor speeds, the instability of the compression system occurs when the opening of the throttle valve decreases to a specific value. The other is that at some constant opening of the throttle valve, whose characteristic curve and the compressor characteristic curves have intersections at the left of the surge line, the instability of the compression system occurs when compressor speed decreases to a specific value. The specific instability conditions under various operating conditions can be obtained through numerical methods, which are crucial for matching the compressor speed with the opening of the throttle valve appropriately to ensure the system safely operate.
c. As the volume of the plenum increases, there is no significant change in the oscillation amplitude of mass flow, and the oscillation frequency of mass flow decreases, the amplitude of pressure drops sharply, and the frequency of pressure pulsation decreases. As the length of the pipe increases, there is no significant change in the oscillation amplitude of mass flow, and the oscillation frequency of mass flow decreases slightly, the amplitude of pressure increases, and the frequency of pressure pulsation decreases slightly.

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Definitions/Abbreviations

GA - genetic algorithm

MG model - Moore-Greitzer model