

A Study on the Characteristics of an Oil-Free Centrifugal Compressor for Fuel Cell Vehicles

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ABSTRACT

The subject of this study is a centrifugal compressor for Fuel Cell Electric Vehicles (FCEV). Recently there is a growing interest in FCEVs since they are considered a realistic solution to environmental regulations for passenger cars to reduce emissions. Water vapor is the only byproduct of a reaction in the Proton Electrolyte Membrane (PEM) fuel cell stack which generates electricity with oxygen from the surrounding air and hydrogen from a fuel tank. Auxiliary systems called Balance of Plant (BOP) serve to provide air and hydrogen to the stack in a correct ratio. The compressor is one of key components of this system because compression of the intake air brings an increase in efficiency and power density of the FCEV. This paper presents the characteristics of a 10 kW class centrifugal compressor with an oil-free bearing system. It consists of a shaft, two airfoil journal bearings and a pair of thrust bearings. They make it possible to obtain a compact, high speed design and proper stability of the compressor without a lubrication system. But, it is difficult to operate this system within a vehicle due to the lack of driving history and operational information. So, a number of tests were carried out to investigate performance, the durability, vibration and thermal characteristics of the compressor with airfoil bearings. A series of startup-shutdown test and base excitation tests were also performed to confirm the applicability of these bearings for vehicles. The experimental facility, conditions and overview of the results were described in this paper.

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INTRODUCTION

The world is faced with two parallel problems of both global warming and energy depletion (e.g. finite limit of fossil fuel resources). The atmospheric carbon dioxide concentration, one of the main causes of global warming has been steadily increasing since the Industrial Revolution. Especially in recent years, the development of China along with other developing countries has accelerated this phenomenon. According to the announcement of the WMO (World Meteorological Organization) carbon dioxide concentrations in the atmosphere in 2013 has increased 1.4 times compared to the early 1900s. In some area the average concentration has been also reported as more than 400 ppm. On the other hand, global energy demand is growing rapidly. Royal Dutch Shell is predicting that the world's consumption of energy will reach 21,000 Mtoe in 2050. This is nearly three times that of 2000. It is known that the world has only 42 years of oil reserves, 61 of gas and 122 of coal at the current rate of consumption. Energy in the world is becoming more and more exhausted. Therefore, countries around the world are expanding its share of renewable energy and strengthen regulations on the fuel efficiency and automobile exhaust to solve these problems. It can be an effective solution because 60 percent of petroleum consumption is made in the transportation sector. Accordingly, many carmakers are introducing new eco-friendly powertrain concepts in the market such as hybrids, plug-in hybrids and battery electric vehicles.

Fuel cell electric vehicle (FCEV) is one of the newly proposed powertrain concepts which is playing an important strategic role in many automobile manufacturers including Hyundai. It is considered a realistic solution to address both environmental regulations for passenger cars and lowering the carbon footprint of the automobile. Water vapor is the only byproduct of a reaction in the fuel cell stack which generates electricity with oxygen from the surrounding air and hydrogen from a fuel tank. So FCEVs have no carbon dioxide, hydrocarbon or nitric oxide emissions in its tailpipe. It also has high power density, moderate operating temperature and quick start-up capability and it can cover long distance driving range, similar to conventional vehicles. Furthermore, the fuel, hydrogen is a clean and efficient energy source which has many advantages. Hydrogen is one of the most abundant energy sources in the universe. It can be obtained through water electrolysis, hydrocarbon reformation or byproduct hydrogen from multiple manufacturing processes. So we expect to be able to build a stable hydrogen supply chain whatever the location of the infrastructure. In addition, it can be fueled quickly (e.g. by using SAE J2601) and stored in a fuel tank of the FCEV easily and its power generation efficiency is quite high, between 50 to 60 percent for the fuel cell system. Therefore, there is a growing interest in FCEV among governments, manufacturers and researchers.

A fuel cell system is composed of a fuel cell stack, an Air Processing System (APS), a fuel processing system and thermal management system. The rest of the system except for the stack is called Balance

of Plant (BOP). It is a complex system that has many components connected each other. So, several advanced researches efforts on the fuel cell system have been performed in past decade [1,2,3,4,5]. These reports suggest simulation models which can predict behavior and performance of the whole system. The feasibility of the system for automotive applications was verified through their efforts. Some of these studies have concluded that the fuel cell system is the most promising candidate for an alternative powertrain in the future. Then a lot of research was carried out for each of the subsystems. Among them, researches on APS have a particularly significant meaning in efficiency and Noise, Vibration and Harshness (NVH) respects because a compressor in APS is one of key components of the fuel cell system. It produces compressed air and sends it to the cathode channel of the stack. It consumes the most parasitic power of the system and it is the only rotating part with a high revolution speed in the FCEV. Compression of the intake air brings an increase in efficiency and power density of the fuel cell system like common internal engines [6]. However, the more power and the faster speeds are needed in order to increase the system air pressure. Therefore it is important to develop a compact, lightweight and efficient air compressor for the FCEV.



Figure 1. A centrifugal compressor used for testing in present study. (Hyundai's 3rd Generation, compressor)

Several types of compressors can be considered for the fuel cell system such as centrifugal compressors, screw or roots-type superchargers. But the subject of this study is a motorized centrifugal compressor since it has an advantage of high pressure ratio despite its small size compared to other types of compressors. The main reason for the advantage is from the centrifugal effect due to the difference of radius between the inlet and the outlet of the impeller. There are several previous studies evaluating the aerodynamic performance and NVH characteristics of centrifugal compressors to apply the centrifugal compressor in the FCEV [7,8,9,10,11]. However, circumstances entered new phase with the introduction of Air Foil Bearings (AFBs) in order to increase its rotational speed. It is in fact possible to make a compact APS and to achieve proper stability of the compressor using the AFB technology for fuel cell applications. Furthermore, higher design speed can bring the sufficient efficiency increase in the low flowrate and high pressure operation range. AFB also has low friction and oil-free nature because it takes advantage of the thin air film lubrication. Especially, the absence of a lubricating oil system offers many advantages to the fuel cell system. It can assist in the chemical stability of the stack (by not utilizing hydrocarbons or

catalyst poisons such as sulfur). However, despite these advantages, it is difficult to operate the AFB system in a vehicle due to the lack of driving history and operational information. In general, AFB is known to be vulnerable to reduced life due to impulsive vibration and the startup-shutdown operations. There has been a significant amount of research on rotor dynamic and tribological characteristics of the AFB itself [12,13,14]. However a full-fledged research for its vehicle applications has only just begun [15, 16]

So, this experimental study was projected to investigate the characteristics of a 10 kW class centrifugal compressor with an oil-free bearing system. Figure 1 shows a centrifugal compressor used for tests in present study. The existing compressor was modified by installing a small gap sensor in front of an impeller to measure the relative distance between a shroud and the impeller. Thermocouples were also installed at monitoring points around AFB system. Then several tests were carried out to investigate aerodynamic performance, the durability, vibration and thermal characteristics of the compressor with AFB. A series of startup-shutdown test and base excitation tests were performed to confirm the applicability of these bearings for vehicle applications. The experimental facility, conditions and results are described in this paper.

SPECIFICATIONS

A centrifugal compressor consists of aerodynamic parts, driving parts and housing. The aerodynamic parts of the present compressor in this study have an impeller, a vaneless type diffuser and a volute. The principle part among them is the centrifugal impeller. It can give a substantial pressure rise in a single stage due to the centrifugal effect. This effect is from its high-speed rotation and the radius difference between inlet and outlet. The impeller is driven directly by the driving parts composed of a shaft, a motor unit and AFB system in current compressor. Specifications of the test centrifugal compressor are listed in table 1. Results of Hyundai's 1st generation compressor are also listed in the same table to show the comparison. In the table it can be seen that the present design Rotations per Minute (rpm) is 100,000 which is 2.5 times speed of the 1st generation compressor. This is possible because of the AFB system. Three pictures on the components of the early AFB system are shown in Figure 2.

The present rotor-dynamic system consists of a shaft, two airfoil journal bearings and a pair of thrust bearings. The first picture in Figure 2 shows an overhung type shaft which has a thrust collar in the opposite side of the impeller. It has permanent magnets on its surface and an Inconel sleeve in order to prevent damage of magnets. This sleeve also plays an important role to form contact surfaces with airfoil journal bearings. Therefore, roughness and hardness of it should be managed in a suitable level. Figure 2 (b) shows several foils of the airfoil journal bearing. It has a conventional multi-layer design with a top foil, a shim foil and a partially split bump foil. This multi-layer design can lead the stiffness and the Coulomb damping increase of journal bearings. A 6 pads air foil thrust bearing is also shown in figure 2 (c). Each pad consists of a top foil and a bump foil welded on a base plate. The circumferential angle of them is 60 degree. There is a ramp in the leading edge of top foil. After this area, the top foil has a flat shape to the end of it. It is important to keep the initial designed shape of top foil because it makes hydrodynamic

pressure on pad and affects the load capacity of the thrust bearing. To do that, it is necessary to select appropriate material thickness and to make close stamping molds for the top and the bump foil. But in general, there are many trials and errors in order to achieve success for this step.

Table 1. Hardware specifications of the existing compressor (3rd gen.) compared with 1st gen. centrifugal compressor.

	1st generation	3rd generation
Design rpm	40,000	100,000
Bearing type	Ball	Air foil
Motor	8 kW class	10 kW class
Cooling type	Air cooled	Water cooled
Design flowrate %	100	62.5
Target pressure ratio %	100	140
Impeller radius %	100	59.2
Weight %	100	71
Volume %	100	60.1

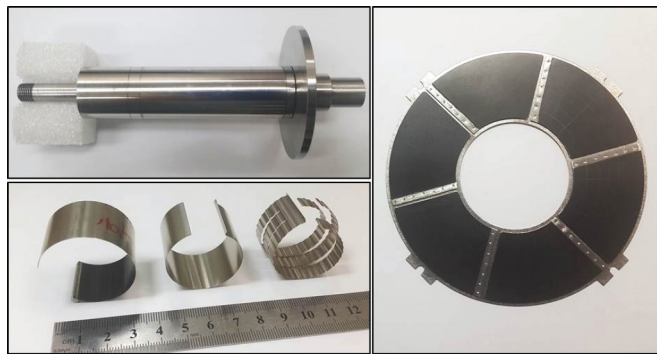


Figure 2. Configurations of (a) shaft, (b) airfoil journal bearing and (c) airfoil thrust bearing in the early model of 3rd generation centrifugal compressor

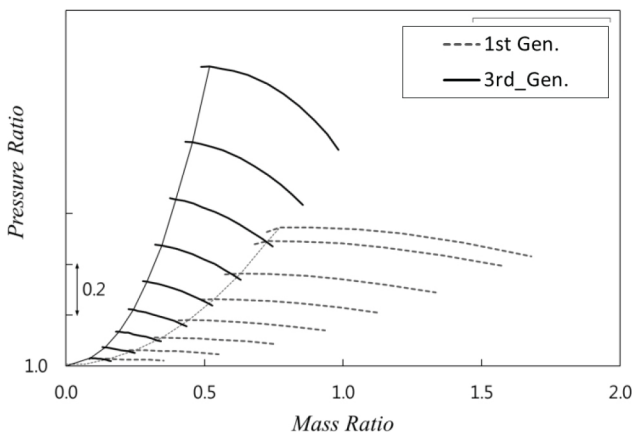


Figure 3. Comparison of aerodynamic performance concepts of 3rd generation compressor versus the 1st generation compressor.

Figure 3 shows pressure maps of the present 3rd gen. compressor and the 1st gen. compressor. It shows the pressure ratio of the two compressors along the mass ratio axis in several RPMs. Test results

of the 3rd gen. compressor are represented in solid lines and those of 1st compressor are done in dotted lines. The mass ratio in x axis is a valueless variable divided by an arbitrary mass flowrate to normalize and hide real scale in this paper. The present generation, the 3rd gen. compressor, was designed to meet the low flowrate and high pressure operation because it can improve the humidity effect and the fuel cell system efficiency in this condition. But the aerodynamic efficiency of an air compressors itself is generally poor due to a low design specific speed in this operating range. Below is a simple equation for the specific speed of compressors.

$$N_s = \frac{N\sqrt{Q}}{(\Delta H)^{3/4}} \quad (1)$$

According to Eq. (1), the only way to increase N_s at the fixed target flowrate (Q) and system head (H) is to increase the design rotational speed (N). To do so, the AFB system was introduced in the present compressor and the results of this attempt are shown in Table 1 and Figure 3. The present compressor is smaller and lighter than the 1st generation while at the same time satisfying new design requirements. The new design flowrate and pressure ratio are respectively 62.5 percent and 140 percent of the previous compressor. It also has a weight of 71 percent and a volume of 60.1 percent compared to the old one though the motor power class is slightly increased by 2 kW and water cooling is applied for effective cooling of the driving parts.

It is possible to make a compact, lightweight air compressor with AFB technology as shown in the results above. However, applying this type of bearings to a compressor for FCEVs has another issue because driving condition is completely different from stationary environment. Irregular vibrations and impulsive forces are applied to the compressor in the vehicle and the startup and shutdown cycles are repeated over and over again during the life of a vehicle. So, several tests were carried out to investigate performance and characteristics of the compressor with AFB in the similar environment with actual driving. A series of startup-shutdown test and base excitation tests were performed. The applicability of these bearings and its resistance to harsh environment of vehicles can be verified through these tests. The results are described in the next chapter in detail.

TEST RESULTS

Aerodynamic Performance and Thermal Conditions

Table 2. Notation of thermocouples and their locations.

TC 1	Coolant air-flow inlet	TC 4	Motor winding end (rear)
TC 2	Front journal outlet	TC 5	Rear journal inlet
TC 3	Neutral point of motor	TC 6	Thrust end