

# Development of Air Supply System for CLARITY FUEL CELL

Tatsuya SUGAWARA\*

Takuma KANAZAWA\*

Yu TACHIBANA\*

Naoki IMAI\*

## ABSTRACT

A compact air supply system has been developed for the CLARITY FUEL CELL fuel cell system in order to make it possible to fit the system under the front hood of the vehicle. The use of a motorized turbo compressor realizing greater quietness than a conventional Lysholm compressor made it possible to reduce the volume of the noise-reducing auxiliary devices by 50%.

Air bearings that do not require oil were used as the compressor bearings based on the necessity of supplying pure air to the fuel cell system.

To address the issue of restriction of the operating range of the compressor as a result of turbocharging, a mixed-flow compressor was used, and two-stage compression was applied. This realized a wide operating range and made it possible to increase air supply pressure 1.7-fold compared to a conventional compressor.

The development of a new inverter using resolver-less control made it possible to do away with the rotation angle sensor in the motor, contributing to increased motor speed and increased compactness. The use of a full-mold power module and a press-fit connection method reduced the size of the inverter unit.

## 1. Introduction

In order to generate power using fuel cells, it is necessary to continuously supply hydrogen and air to the generating surfaces within the fuel cell. Because of this, fuel cell systems can be broadly broken down into the four systems shown in Fig. 1.

While hydrogen is supplied to the fuel cells from the onboard hydrogen tanks following depressurization in the hydrogen supply system, air is sent to the fuel cells following intake and compression by an air compressor in the air supply system.

Since the development of the FCX<sup>(1)</sup> in 2002, Honda has used motorized Lysholm compressors as the air compressors in its fuel cell vehicles. For the CLARITY

FUEL CELL, however, the aim was to reduce the size of the system in order to make it possible to fit the fuel cell system under the front hood<sup>(2)</sup>, leading to the development of a next-generation air supply system using a motorized turbo compressor (Fig. 2).

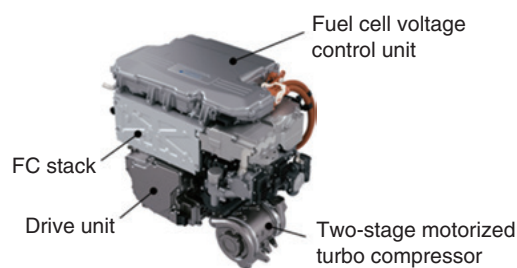


Fig. 2 Downsized fuel cell powertrain

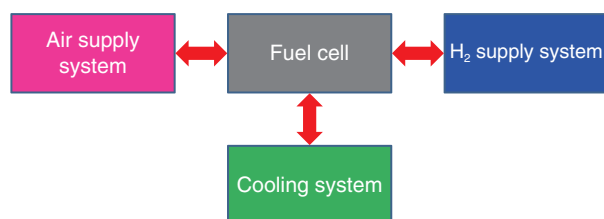


Fig. 1 Overview of fuel cell system

## 2. Development Aims

Conventional Lysholm compressors release air following its compression by the rotors in the compressor; the noise produced by the discharge of air therefore increases in proportion to the operating pressure. Because

\* Automobile R&D Center

of this, the capacity and volume of noise-reducing devices used to attenuate this noise also increase in proportion to the operating pressure of the compressor. Turbocharged compressors, by contrast, do away with the internal compression process of conventional Lysholm compressors, and produce a low level of discharge noise. The use of a turbocharged compressor would mean that it would be possible to reduce the number of noise-reducing devices and thus reduce the size of the system even if the operating pressure was increased.

In addition, increasing the pressure of the air supplied to the fuel cells would increase the oxygen partial pressure, reducing the decline in the voltage of the fuel cells when operating at high power. As a result, it would be possible to increase the total power of the fuel cell system as shown in Fig. 3, even when the increase in the power consumption of the air compressor necessary for increasing the air pressure is subtracted. It was thought that this would reduce the necessary number of cells in the stack, and thus contribute to reduced size and cost.

Increasing the operating pressure would also increase the relative humidity inside the stack, as shown in Fig. 4. This would reduce the necessary amount of humidification,

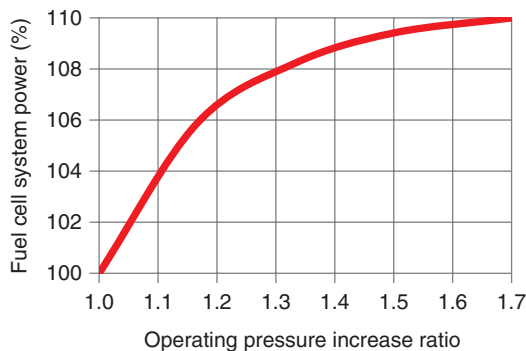


Fig. 3 Correlation between cathode operating pressure and fuel cell system power

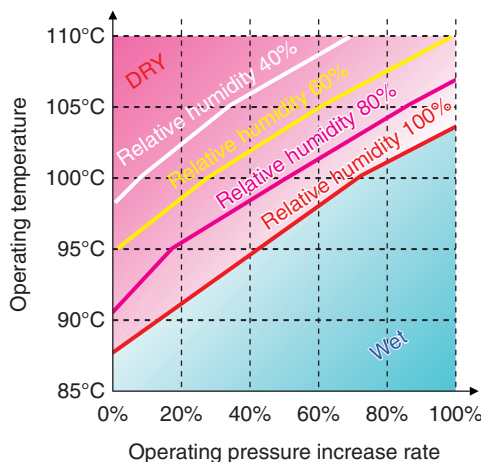


Fig. 4 Correlation between stack humidity and pressure and temperature

making it possible to reduce the size of the humidifier.

An increase in operating pressure would also make it possible to maintain an appropriate level of stack humidity even under conditions in which operating temperature increased. This would mean that the generation performance of the fuel cells could be maintained even in scenarios in which operating temperature increases, such as steep hill climbing, when there is little breeze from driving or when the cooling ability of the radiator is low, making it possible to maintain a high level of dynamic performance.

Based on the considerations above, the aims for the development of the air supply system for the CLARITY FUEL CELL were set as follows.

- (1) Reduction of the necessary number of fuel cells through the realization of increased fuel cell power by increasing air supply pressure, reducing the size and cost of the system.
- (2) Reduction of the size of the humidifier and expansion of the high-temperature operating range of the fuel cells by means of the reduction of the necessary amount of humidification through the realization of increased air supply pressure.
- (3) Scrapping of auxiliary noise-reducing devices as a result of the realization of increased quietness through the application of a motorized turbo compressor, and the consequent reduction in size of the air supply system.
- (4) Development of an inverter capable of sensor-less control, realizing a resolver-less motor able to be reduced in size, helping to enable the system to be fit under the front hood.

### 3. Characteristics of Two-stage Motorized Turbo Compressor

Figures 5 and 6 respectively show an external view and a sectional view of the two-stage motorized turbo compressor developed jointly with Honeywell.

This compressor configuration has the following characteristics.

- (1) Air bearings are employed as the bearings.
- (2) The unit is a two-stage turbo compressor, provided with a low-pressure-side compressor and a high-pressure-side compressor at the respective ends of the rotor.



Fig. 5 Two-stage motorized turbo compressor

- (3) The turbocharging of the compressor increases quietness.

### 3.1. Configuration of Bearings

Oil-lubricated bearings are normally used for turbochargers in internal combustion engines. However, there was a concern that when using a turbo compressor in a fuel cell system, oil flowing from the bearings might poison the fuel cells, causing a decline in generation performance. Air bearings, which are used in the turbochargers in aircraft air cycle systems, were used for the first time in an automotive application. Figure 7 shows the structure of the radial air bearings as an example of the bearing configuration.

Figure 8 shows the principle of rotor lift-off. As the rotor rotates, the viscous action of air forces air into a wedge-shaped gap, generating pressure (dynamic pressure), lifting the rotor off the bearings.

Following the lift-off of the rotor, the generated pressure is transmitted to a bump foil via a top foil, as shown in Fig. 9. Fluctuations in pressure are absorbed by the deformation of the bump foil, and the fluctuations are attenuated by the friction force between the foils. This makes it possible

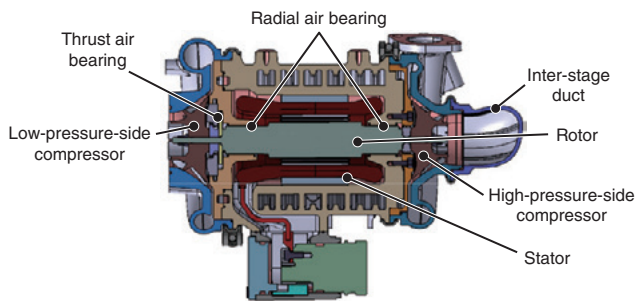


Fig. 6 Sectional view of motorized turbo compressor

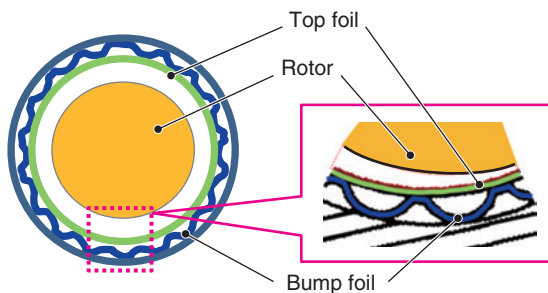


Fig. 7 Structure of radial air bearing

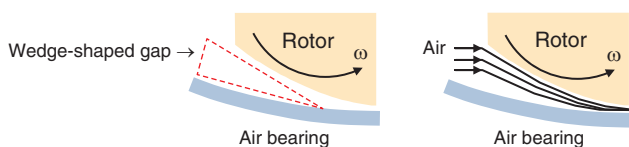


Fig. 8 Rotor lift-off mechanism

to maintain an optimal thin air layer thickness, even with fluctuations in pressure due to fluctuations in rotor speed, thus maintaining the lift-off of the rotor.

### 3.2. Compressor Configuration

In order to reduce the size of the fuel cell system, it was necessary to increase the pressure of the air supplied to the fuel cells. In addition, because it is necessary to control pressure and flow rate in response to changes in the operating environment (for example load, temperature, or atmospheric pressure), and to control transient states, as exemplified by acceleration and deceleration, it is important to help ensure a wide operating range in an air compressor used in a fuel cell system.

Figure 10 shows standard turbo compressors. Centrifugal compressors of these types are widely used as turbo compressors in engine applications. Because all the fluid flows out from the peripheries of the impeller in a centrifugal compressor, the units are able to realize a considerable pressure increase<sup>(3)</sup>. However, when the flow rate is reduced, the system pressure and flow rate begin to fluctuate<sup>(4)</sup>, and surges occur that restrict the operating range.

In contrast, while the axial compressors used in jet engines are able to realize a high flow rate, these compressors are not able to achieve a high pressure increase using a single-stage impeller. It is necessary to use a multi-

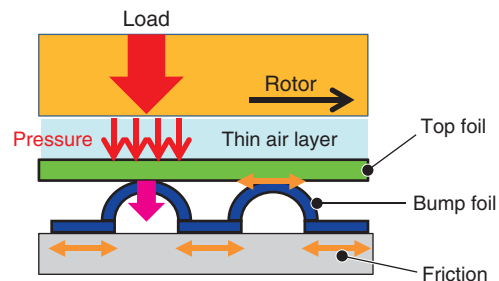


Fig. 9 Operation of air bearing

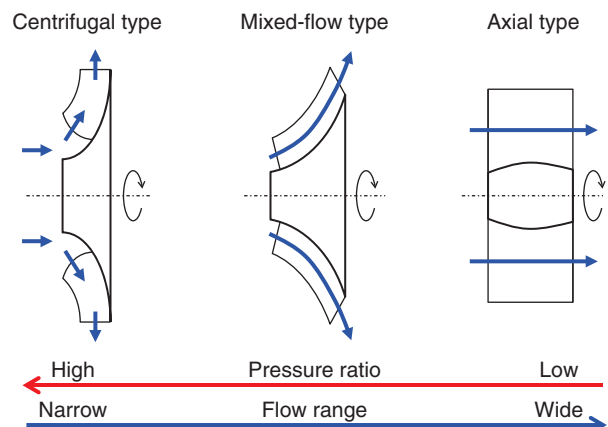


Fig. 10 Compressor wheel type

stage impeller when a high pressure increase is important.

In order to realize a wide operating range, a mixed-flow compressor configuration offering characteristics intermediate between those of the centrifugal and axial compressor types was adopted. A two-stage configuration was applied, making it possible to balance a high ratio between intake pressure and discharge pressure (pressure ratio) with a high flow rate (Fig. 11).

Figure 12 and Table 1 compare this configuration with a one-stage centrifugal compressor. The use of the mixed-flow compressor made it possible to balance a 1.7-fold increase in the compression ratio against the centrifugal compressor with the realization of a wide operating range.

### 3.3. Realization of increased Quietness via Turbocharging of Compressor

Because they do not use internal combustion engines, fuel cell vehicles are quiet during operation. Given this, it is important to reduce the operating noise of the air compressors used in fuel cell vehicles.

Figure 13 shows the configuration of a conventional Lysholm compressor<sup>(5)</sup>. Lysholm compressors compress air internally between a pair of rotors. Because intake and discharge are intermittent, pulsation noise is generated at the inlet and outlet sides. In addition, because the rotors

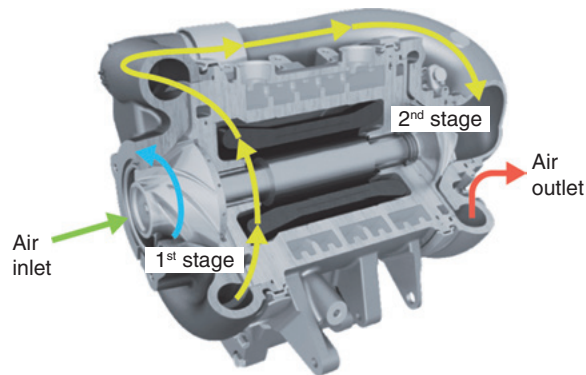


Fig. 11 Internal air flow of two-stage motorized turbo compressor

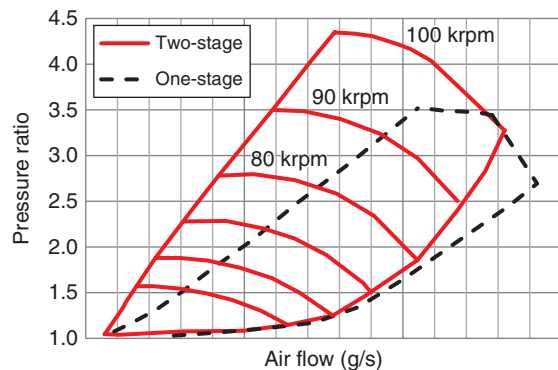


Fig. 12 Performance map

Table 1 Specifications

|                        | One-stage   | Two-stage  |
|------------------------|-------------|------------|
| Wheel type             | Centrifugal | Mixed-flow |
| Maximum rotation speed | 100 krpm    | 100 krpm   |
| Maximum pressure ratio | 3.5         | 4.2        |

are driven by gears, gear noise also infiltrates the cabin as compressor operating noise. This has necessitated the use of a large number of noise-reducing auxiliary devices in order to maintain the quietness during operation that is a characteristic of fuel cell vehicles.

The application of the new turbo compressor has reduced pulsation, making it possible to reduce noise on the inlet and outlet sides as shown in Figs. 14 and 15 respectively.

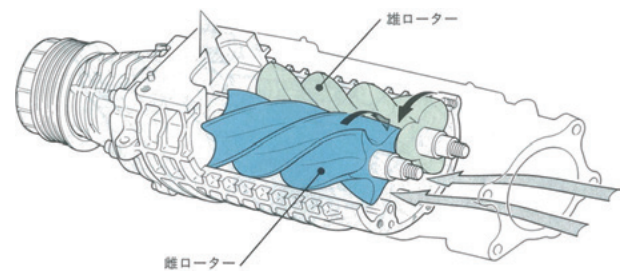


Fig. 13 Cross-section of Lysholm compressor

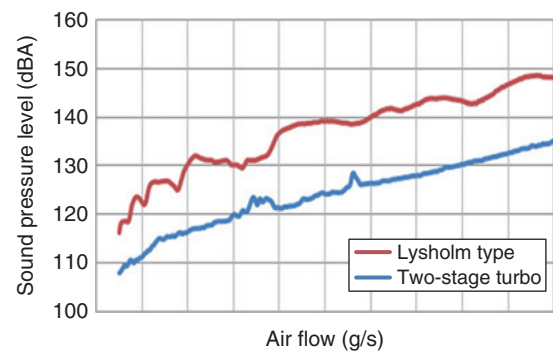


Fig. 14 Inlet noise comparison

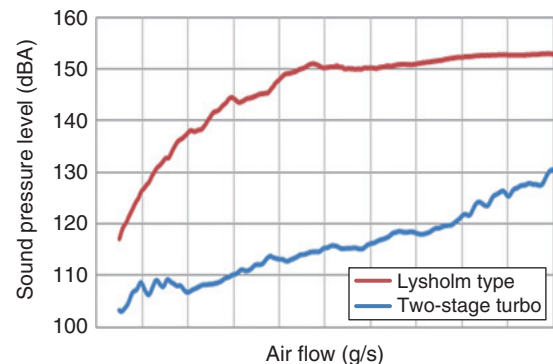


Fig. 15 Outlet noise comparison

In addition, while the twin rotors in conventional Lysholm compressors are driven by gears, using the same shaft for the compressors and the rotors in the new unit has made the gears unnecessary, making it possible to realize the reduction in radiation noise from the unit shown in Fig. 16.

Increasing the quietness of the compressor made it possible to reduce the size of the resonator used to address inlet pulsation noise and do away with the silencer used to address outlet pulsation noise and the cover for reduction of radiation noise, which previously occupied a considerable amount of space under the front hood. As a result, it has been possible to integrate the auxiliary noise-reducing devices with the air cleaner, as shown in Fig. 17, reducing volume by 50% against the previous model, the FCX Clarity<sup>(6)</sup>.

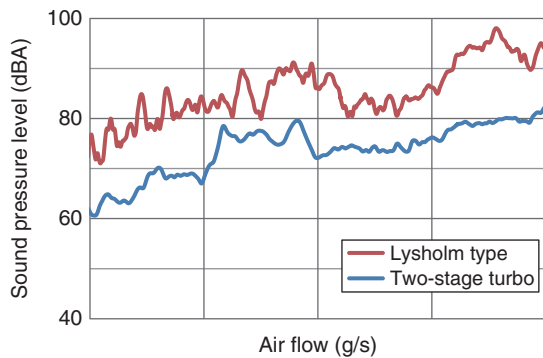


Fig. 16 Comparison of radiation noise near compressor

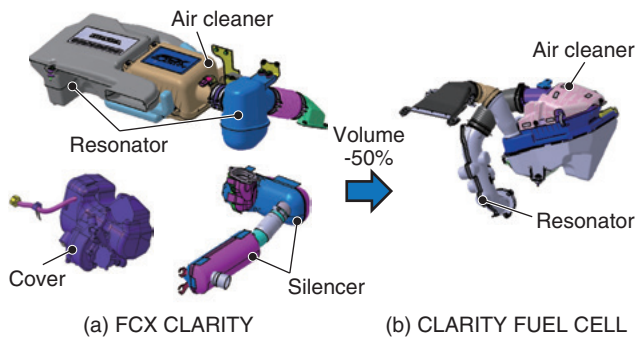


Fig. 17 Downsized noise reduction devices

#### 4. Drive Inverter for Two-stage Motorized Turbo Compressor

Figure 18 shows the inverter unit jointly developed by Honda and BRUSA. The unit has the following characteristics.

The inverter is integrated with the Intelligent Power

Unit (IPU) box to help enable fitting in a limited space, and is provided with devices capable of high-speed switching and cooling structures to help enable sensor-less control at a compressor shaft speed of 100,000 rpm.

##### 4.1. Integration of Inverter and IPU Box

When an inverter unit is fitted in a vehicle, it is necessary for the packaging to satisfy two criteria.

The first of these is that the direct-current high-voltage cable (DC cable) connected to the primary side of the inverter unit is integrally connected with the IPU box outside the cabin. The other is a layout that helps to ensure that the unit's case is not damaged in any of the crash tests that the vehicle undergoes.

It was necessary to fit a package of a size that satisfied these conditions in an area at the front of the IPU box in which there would be no incursion from rigid bodies during crash tests. Following the satisfaction of performance demands, a dedicated inverter that could be installed in this area was developed, and its packaging was integrated with the IPU box (Fig. 19).

To help ensure the safety of technicians conducting maintenance, the configuration used makes it unable to access the area in which the DC cable is connected when the unit is fitted in the vehicle. A layout in which the DC cable is directly extended from the IPU box to the inverter unit was necessary in order to realize this configuration. The waterproof performance of the IPU box was an issue in this. To help ensure waterproof performance, a flexible rubber duct was used to house the connection between the

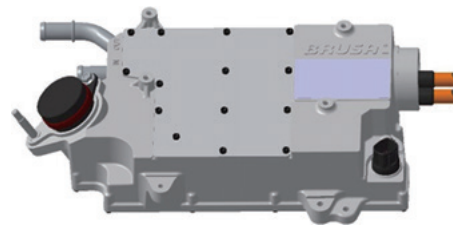


Fig. 18 Air pump inverter unit

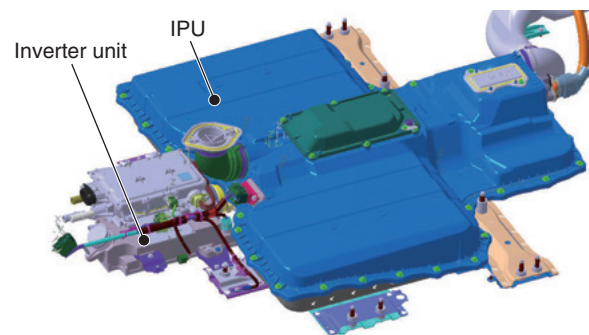


Fig. 19 Potential area for fitting of controller unit

IPU box and the inverter unit (Fig. 20). In addition, the fact that the inverter unit would be positioned under the floor of the vehicle, where it could be submerged in water (Fig. 21), necessitated consideration of waterproofing and corrosion prevention in the design of the unit. An aluminum material possessing a high level of rust resistance was therefore used for the inverter case. Formed-in-place-gaskets (FIPG) were used in the gap between the case and the lid for waterproofing as an anti-corrosion measure.

#### 4.2. High-speed Switching Technology and Technologies for Reduction of Size

The following three element technologies were used to reduce the size and increase the efficiency of the inverter unit.

The use of a full-mold module increased heat radiation, and the use of a press-fit connection made it possible to reduce the size of the unit. The size of the motor was also reduced through the use of sensor-less control.

The use of a power module in which a direct copper-bonded (DCB) substrate was sealed by means of transfer molding (Figs. 22 and 23) reduced thermal resistance from the semiconductor chip to the base plate, realizing highly efficient heat radiation. This made it possible to realize switching at 24 kHz, a frequency exceeding the switching

frequency of conventional insulated gate bipolar transistors (IGBT).

With regard to the press-fit connection used for the power module pin, the high-pressure insertion of the press-fit pin into the base plate through-hole to form an electrical connection with the power base plate helps to eliminate any decline in reliability due to solder cracks originating in heat impact. The size of the unit was also reduced through simplification of the wiring and reduction of the distance between parts. In order to reduce development time, a press-fit terminal for which design and production licenses based on the IEC standards could be obtained was used. The clarification of the relationship between the value of temperature increase and the value of contact resistance in the area of contact with high current-carrying parts (Fig. 24), which is important from the perspective of specifications, and management on this basis, has helped to ensure the durability and reliability of the electrical connection sections.

24 kHz, which is outside the audible range, are used as the switching frequency for sensor-less control, and a single electrode couple has been used in the motor. This has reduced switching noise and helped to ensure stable motor control at the maximum compressor speed of 100,000 rpm.

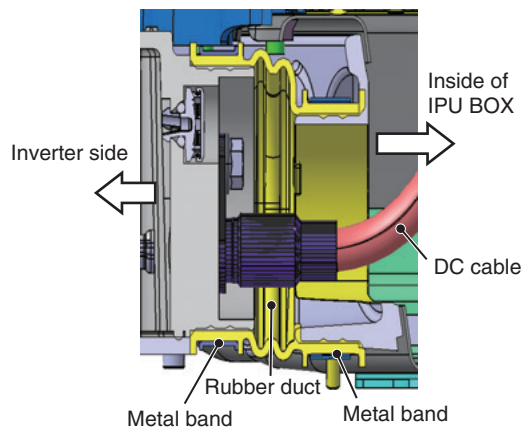


Fig. 20 Sectional view of duct



Fig. 21 Inverter mounting position

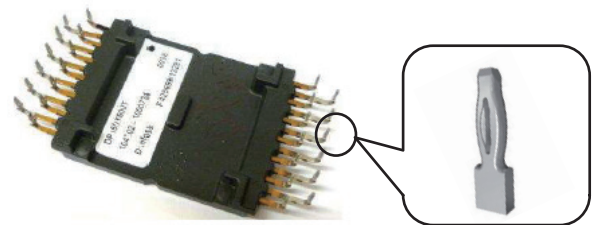


Fig. 22 Full-mold module and press-fit pin

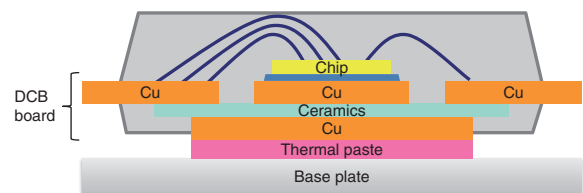


Fig. 23 Sectional image of full-mold module

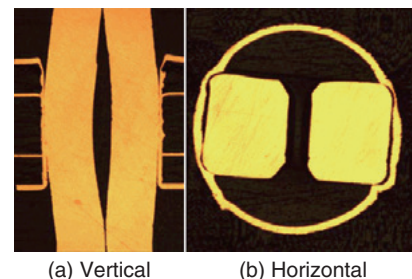


Fig. 24 Cross-section of press-fit connection

Figure 25 shows the control values for sensor-less control and the behavior of the control at different compressor speeds. This control conducts power regeneration during deceleration using PWM control in order to reduce the amount of time that the rotors stop rotating, helping to realize a high level of responsiveness during both acceleration and deceleration.

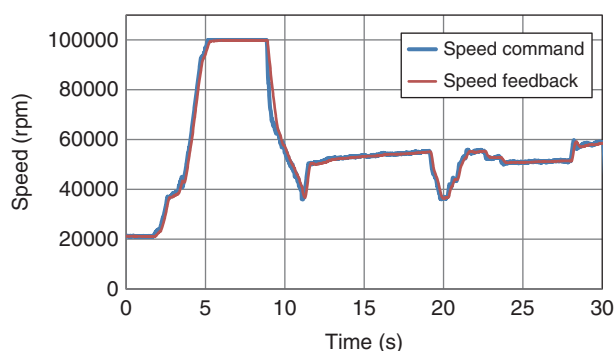


Fig. 25 Rotor speed behavior with sensor-less control

## 5. Conclusion

A two-stage motorized turbo compressor has been developed with the aim of increasing the pressure of air supplied to a fuel cell system and increasing quietness. The following outcomes were obtained.

- (1) The use of two-stage compression in a mixed-flow compressor has made it possible to realize a 1.7-fold increase in air supply pressure compared to a conventional compressor.
- (2) Air bearings were used to realize high-speed bearings that do not require oil, making it possible to use a turbo compressor in a fuel cell system supplied with pure air.
- (3) The use of the motorized turbo compressor made it possible to reduce the volume of the auxiliary noise-reducing devices by 50%.
- (4) To help ensure collision safety and electrical safety, a full-mold module and press-fit connection technology have been used in the inverter, which is integrated with the IPU box. The application of these technologies made it possible to realize a compact, high-speed inverter using sensor-less control, contributing to the reduction of motor size.

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## ■ Author ■



Tatsuya SUGAWARA



Takuma KANAZAWA



Yu TACHIBANA



Naoki IMAI