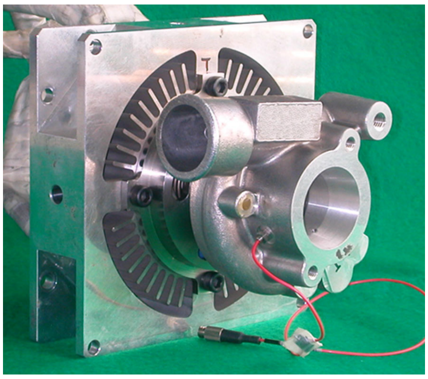
Development of Electric Supercharger to Facilitate the Downsizing of Automobile Engines



YUKIO YAMASHITA*1 SEIICHI IBARAKI*2

KUNIO SUMIDA*1 MOTOKI EBISU*3

BYEONGIL AN*4 HIROSHI OGITA*5

To satisfy both environmental regulations and drivability requirements, high-level control of automobile engines is currently in demand, and electrification is in progress. An electric supercharger, in which a supercharging compressor is driven by a high-speed motor instead of an exhaust turbine or belt, eliminates turbo lag by making use of the motor's high-speed response. An engine with an electric supercharger offers comparable fuel consumption to a naturally aspirated engine, and is expected to facilitate the downsizing of engines. In this paper, we introduce the electric supercharger developed by Mitsubishi Heavy Industries, Ltd. (MHI), including bench test results exhibiting a high-speed response of 1.0-s acceleration time to attain a compressor operating point rated at 2 kW, 140,000 rpm.

1. Introduction

With the ongoing movement toward global environmental protection, regulations controlling the exhaust emissions and fuel consumption of automobiles are being enforced. Turbochargers have improved the performance of diesel engines; currently, almost all diesel vehicles are equipped with turbochargers. More and more gasoline engines are also being fitted with turbochargers to decrease weight and increase efficiency[1].

In recent years, engine controls have become widely diversified for the sake of both the environment and operating performance. Variable geometry (VG) turbochargers, which can vary the turbine capacity in response to the engine load, are becoming increasingly popular. Also, electrification (and the installation of various electrical devices in automobiles) has produced the present generation of hybrid and electric vehicles, and progress continues. Batteries are also expected to improve in response to this trend. Current electrification projects impacting turbochargers include the application of electronic control actuators. Moreover, advances in power electronics have led to the development of ultra high speed motors/generators with a capacity of 100,000 rpm or higher, which are now available for use in turbochargers.

In an electric supercharger the compressor is directly connected to an ultra high speed motor, and the compressor boost pressure is controlled by the motor speed, independent of the exhaust turbine. This supercharger is expected to contribute to lower fuel consumption, the reduction of exhaust loss, and the downsizing of engines.

2. Classification of electric turbochargers

Electric turbochargers equipped with ultra high speed motors are classified into two types. One of these is a hybrid turbocharger[2], in which an ultra high speed motor is contained in a conventional turbocharger. The conventional turbocharger supplies pressurized air to the engine with a compressor rotated by a turbine driven by engine exhaust. The motor/generator integrated

*1 Nagasaki Research and Development Center, Technical Headquarters
*2 Manager, Nagasaki Research and Development Center, Technical Headquarters
*3 Manager, Turbocharger Engineering Department, General Machinery & Special Vehicle Headquarters
*4 Turbocharger Engineering Department, General Machinery & Special Vehicle Headquarters
*5 MHI Sagami High-tech Ltd.

into the turbocharger assists the rotation under low-speed engine conditions, when the exhaust energy is insufficient, and improves the weak point of the transient response delay of the turbocharger (i.e., turbo lag).

Under high-speed engine conditions, excess gas energy from exhaust is recovered as electricity and is utilized for charging the battery or assisting an engine with an integrated starter generator (ISG).

The other type of electric turbocharger with an ultra high speed motor is the newly developed electric supercharger, which does not utilize exhaust. The centrifugal compressor supplies pressurized air to the engine solely in response to the torque of the high-speed motor that drives it. **Figure 1** is a diagram of the electric supercharger system, and **Figure 2** shows the prototype. The electric supercharger is also effective for constructing a two-stage turbocharger combined with another turbocharger. **Figure 3** shows the results of a response analysis of a 1.4-liter gasoline engine accelerating to the target torque. The transient time has been reduced by 35% compared to that of a conventional turbocharger.

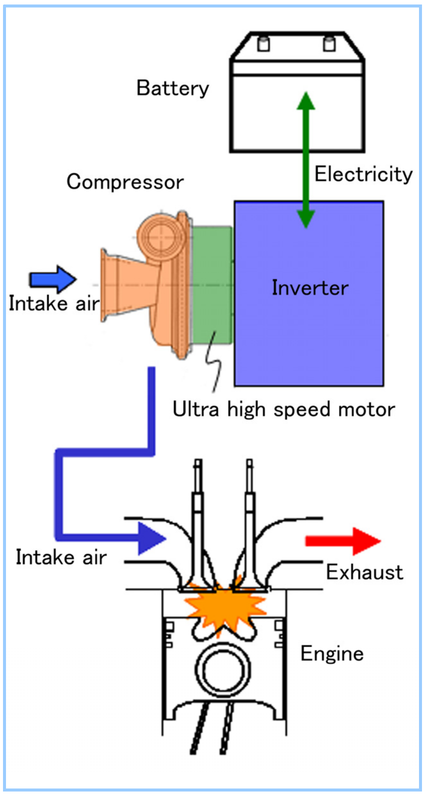


Figure 1 Electric supercharger system
The ultra high speed motor on the electric supercharger rotates the compressor in response to engine requirements for intake air pressure, receiving electricity from the battery through the inverter.

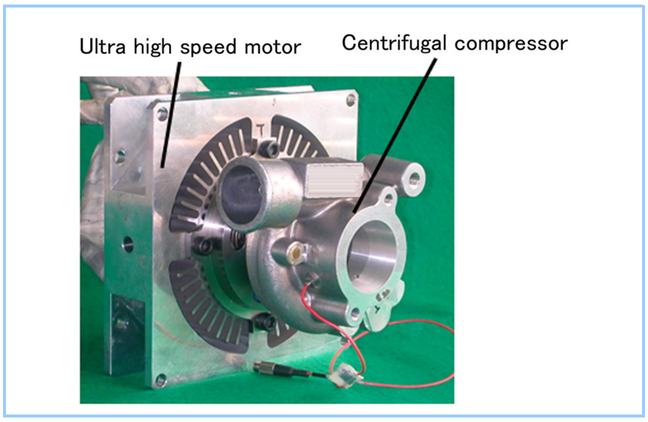


Figure 2 Electric supercharger
The prototype of the electric compressor is shown. The ultra high speed motor drives the centrifugal compressor.

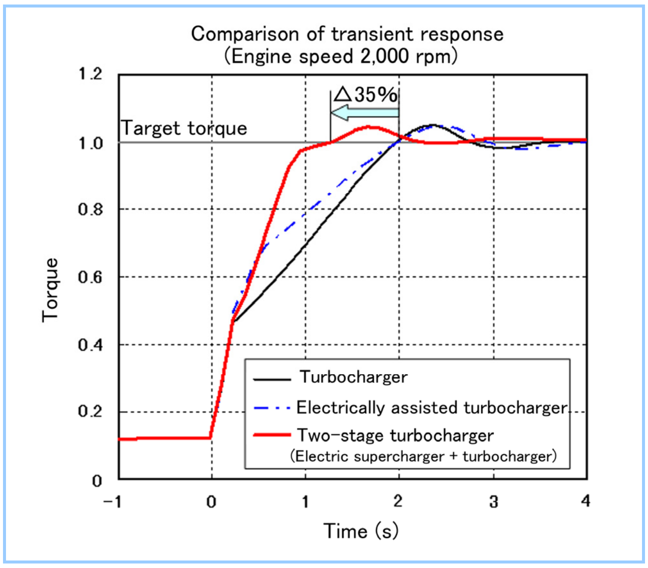


Figure 3 The results of the response analysis of the engine
The torque response of a 1.4-liter gasoline engine with electric supercharger

3. Development of the electric Supercharger

3.1 Development concepts

To be applicable to current vehicles, the concepts are as follows:

- The electric power source is 12 V DC.
- The compressor, motor, and inverter are integrated into one body.
- No separate fan or water-cooling device is used for cooling.

3.2 Construction and features

The electric supercharger prototype consists of a centrifugal compressor impeller and a high-speed motor rotor, supported with a ball bearing for improved response and reduced friction. Grease lubrication eliminates the need for lubrication oil piping. To improve the transient response by reducing rotor inertia, the rotor has been kept as small in diameter and as long as possible.

Compressor intake air is utilized to cool the motor and inverter. Because the motor and inverter are upstream of the compressor intake, they are cooled whenever the electric supercharger rotates. The cooling airflow varies with the compressor working point and is favorable to high heat reduction in the motor and inverter when the flow volume is large. Using loss calculations based on finite element method (FEM) magnetic field analysis and circuit simulation, and using flow velocity distribution calculations in the cooling flow channel based on computational fluid dynamics (CFD) analysis, the temperature increases in the motor and inverter can be predicted, and the flow channel can be improved. **Figure 4** shows the results of the CFD flow velocity distribution calculations. The cooling-channel pressure loss can also be calculated to improve the channel shape and to avoid excessive increases in the power required for the motor and inverter.

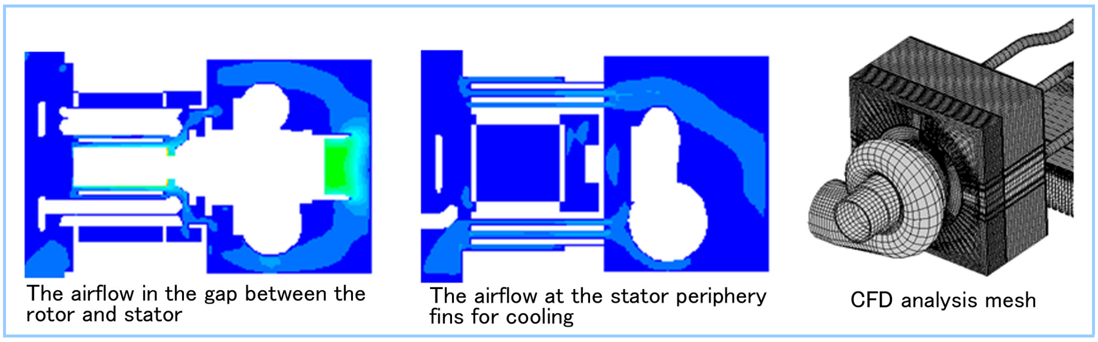


Figure 4 Flow distribution calculations for motor cooling air by CFD
Calculation of cooling air velocity in the motor which is located in the path of inlet airflow of the compressor

3.3 Power electronics technology

3.3.1 Ultra high speed motor

The motor is a three phase permanent magnet synchronous type. Samarium-cobalt rare-earth magnets (which are strongly magnetic and heat resistant) are used for the rotor to minimize the size of the motor. The magnets are held in place against rotor centrifugal force (which is especially important in ultra high speed motors) by surrounding them with cylindrically laminated, carbon-fiber reinforced plastic (CFRP) sheets. In carbon-cylinder manufacturing, flaking and expansion are avoided by considering the fiber direction and trimming the edge of the sheet. The rotor was spin-tested and verified at 1.2 times the rated rotational speed without breakage. **Figure 5** shows a sectional view of the rotor retention ring after the increased temperature test with the motor running. The rotor appears robust, without deformation or carbon flaking. The stator coil has a single turn per phase and a star connection. A single turn per phase is the only way to realize the range of values for the back electromotive force (EMF) constant and the inductance that provides the required torque under low-voltage ultra high speed conditions. **Figure 6** shows an external view of the stator.

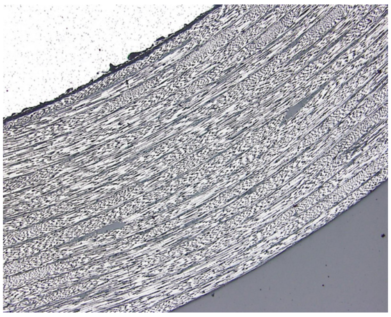


Figure 5 Sectional view of the rotor-retention ring after the operating test
The rotor appears robust, without deformation or carbon flaking.

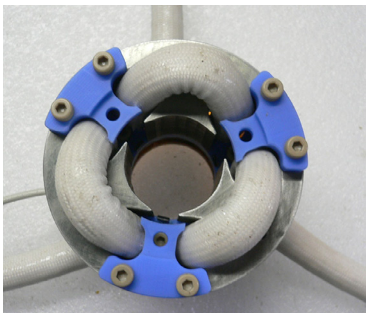


Figure 6 Motor stator
The coil has a single turn per phase to satisfy low-voltage ultra high speed specifications.

The rated output of the motor is 2 kW, 140,000 rpm. To achieve a high-speed response, instant double overload is permitted. By FEM magnetic-field analysis of the motor, using the electric-current waveform acquired from the inverter circuit simulation, the loss (including the eddy current in the magnet) is calculated.

3.3.2 Inverter

The inverter is a general pulse-width-modulation (PWM) voltage source type. A field-effect transistor (FET), which allows high-speed switching, is used as a semiconductor switching device. A general-purpose microcomputer is employed for the motor control. The fundamental electrical frequency exceeds 2 kHz, and the processing speed of the microcomputer is insufficient to apply rigorous field-oriented control. A voltage-to-frequency (V/f) control that includes a partial closed-loop current control has been adopted. Rotational position sensor such as Hall-effect devices and resolvers are not used, and a sensorless control with position estimation based on the detected current has been adopted. To avoid loss of synchronization or over current caused by a position estimation error in a high-speed response, a current-phase correction control based on the current and rotational speed has also been employed.

3.4 Test results

The bench test results of the electric supercharger with modified compressor impeller and the motor and inverter described previously, are presented here. The compressor load was varied by opening and closing the outlet valve in the compressor discharge pipe.

Figure 7 is a graph of the typical working-point measurements, showing the compressor characteristics on a Total Pressure Ratio to Compressor Performance map. A 1.0 second response from the idle speed of 10,000 rpm to the rated speed of 140,000 rpm is verified near the surge-line side, the choking side, and on the impeller maximum efficiency line. **Figure 8** shows the response curve on the impeller maximum efficiency line. The motor output is 2 kW, and the speed is 140,000 rpm at the working point.

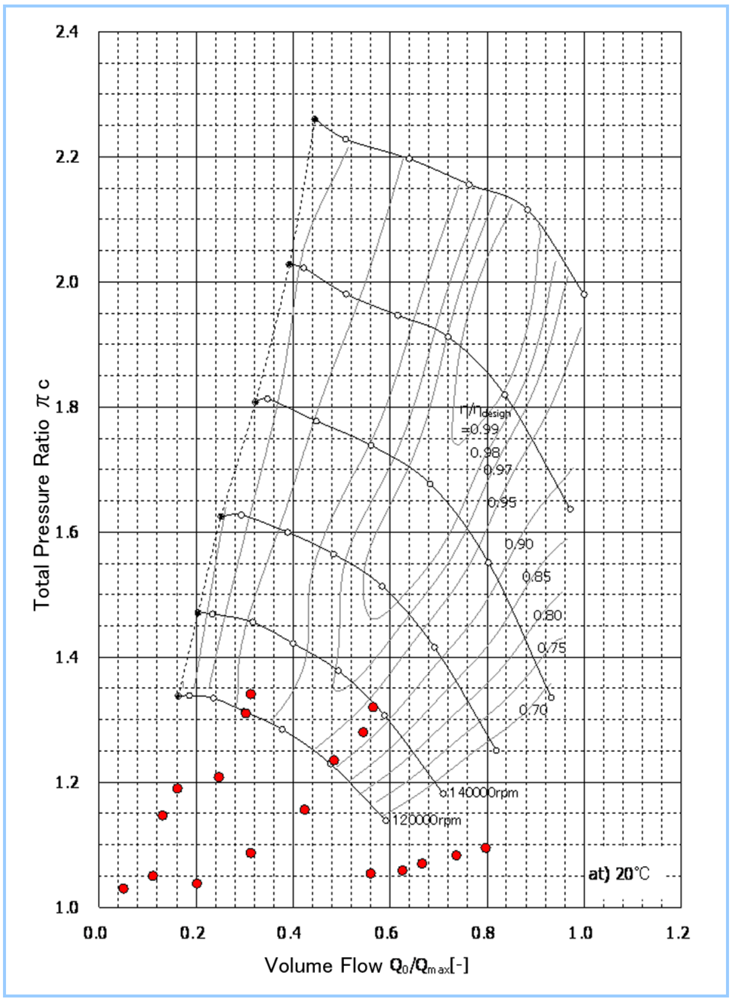


Figure 7 Measured working points of the compressor
A wide working range was tested by adjusting the area of the opening of the compressor outlet valve.

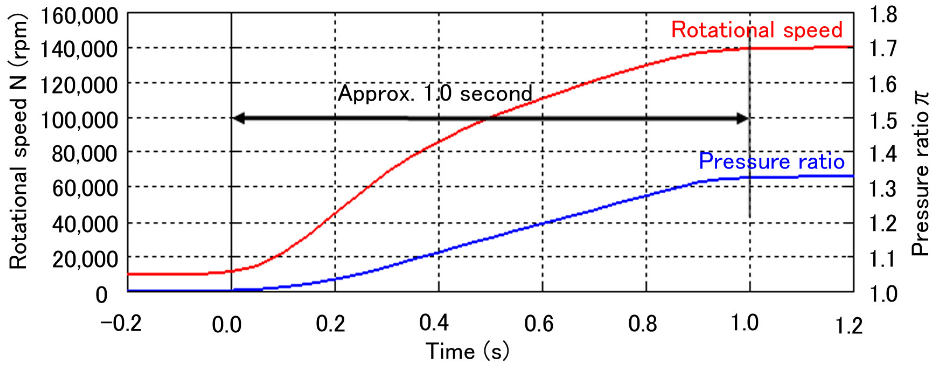


Figure 8　Quick response curve of the electric supercharger
A response time of ~1.0 second to the compressor working point of 2 kW, 140,000 rpm (the rated point for the motor) was verified.

Figure 9 shows one of the measured motor-current waveforms, illustrating rapid acceleration from the idle speed of 10,000 rpm to the rated speed of 140,000 rpm. Control is achieved from low to high rotational speeds without loss of synchronization. Even at high rotational speeds, the current waveform is kept close to sinusoidal by the PWM control drives the motor.

Figure 10 shows the temperature changes at the measured points on the motor and inverter. All of the temperatures are below the allowable limit, and the previous FEM and CFD studies were verified. The present thermal design is based on continuous operation, and reduced size is possible for short-term or intermittent operation.

The shaft vibration was measured at the end of the compressor shaft, and the main component (first order of rotational speed) did not exceed the limit during operation.

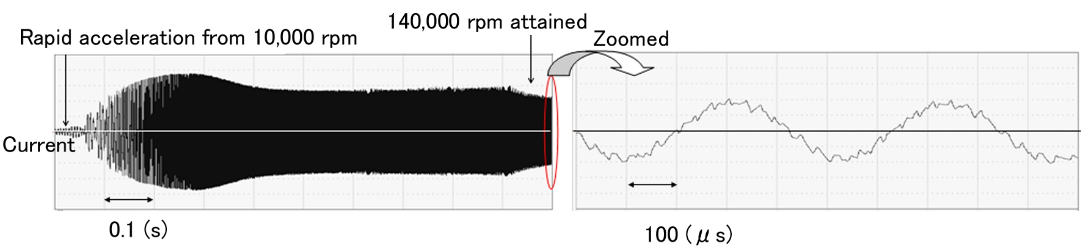


Figure 9　Motor current waveform
At high speeds, the current waveform was close to sinusoidal by PWM control

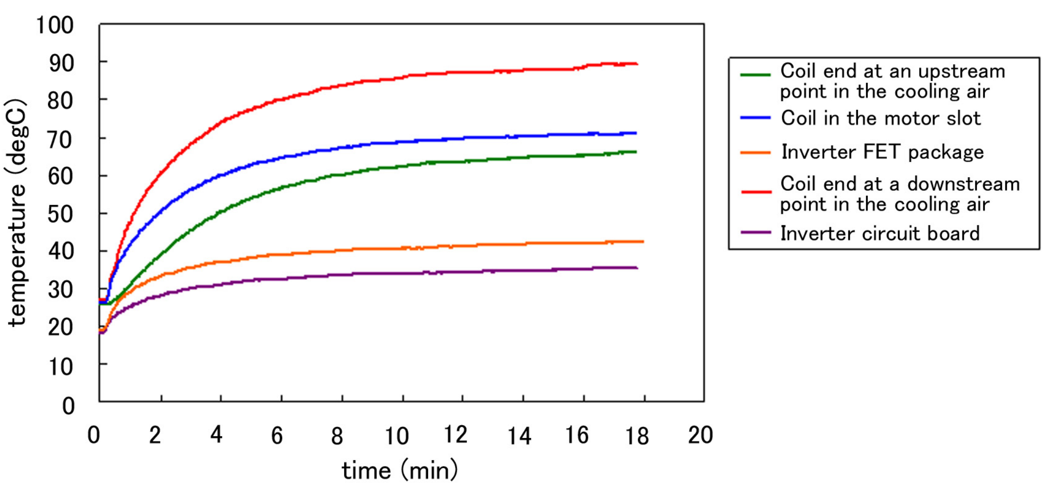


Figure 10　Temperature changes at the measured points on the motor and inverter
Temperature changes at the measured points during 2 kW, 140,000 rpm operation. All points had a temperature below the calculated allowable limit.

4. Problems and future prospects

The bench test of the 12-V electric supercharger prototype demonstrated a high-speed response of 1.0 second, and its effectiveness for eliminating turbo lag was experimentally verified. For application to automobiles, the following items need to be addressed:

- Durability verification of parts such as the bearing and the semiconductor element
- Reduction of the dimensions, cost, and noise
- Establishment of design goals for the electric supercharger output specifications, and an operational pattern to optimize the system and the corresponding control method
- Establishment of an electric power management system in which the electric supercharger works compatibly with other electrical equipment in vehicle.

5. Conclusion

A prototype of the electric supercharger (a promising new turbocharger technology in the face of stricter exhaust and fuel consumption regulations) was produced and tested to verify its technical possibilities. In addition to the electric supercharger, an electrically assisted turbocharger and an electric compressor for fuel cells are being developed as applications of the ultra high speed motor.

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