Development of Two-stage Electric Turbocharging system for Automobiles

BYEONGIL AN*1 NAOMICHI SHIBATA*2

HIROSHI SUZUKI*3 MOTOKI EBISU*1

Engine downsizing using supercharging is progressing to cope with tightening global environmental regulations. In addition, further improvement in fuel consumption is expected with such applications as ultra-high EGR, Miller cycle, and lean combustion. Mitsubishi Heavy Industries, Ltd. (MHI) has developed a two-stage electric turbocharging system to balance better drivability and improved fuel consumption by increasing the turbocharging pressure and improving the transient response.

1. Introduction

Engine downsizing/downspeeding through supercharging is progressing to cope with annually enhanced improvement in fuel consumption and exhaust gas. Downsizing through direct injection and supercharging has been developed mainly in European countries where the CO_2 regulations are the most stringent, and it has expedited the increase of the turbocharger installation rate in other areas. Diesel vehicles are supposed to satisfy the CO_2 and exhaust gas regulation standards in 2021. However, gasoline vehicles are still not able to meet the standards even in the case of low-fuel consumption vehicles with supercharged downsizing, and further measures are required. The adoption of WLTC (Worldwide harmonized Light duty driving Test Cycle) is planned globally in and after 2017, and new regulations taking actual driving conditions into consideration are being discussed. Turbochargers are required to provide a further boost pressure and better response, as well as robust and easy to operate characteristics, for this purpose.

Existing turbochargers have a time-lag and EGR response delay, and proper control is difficult. In addition to existing exhaust gas turbochargers, a turbocharger with electric power assist utilizing the high-speed response of an electric motor, which improves both the fuel consumption by significant downsizing and the transient response, is recently expected to be put into practical use.[1]

The electric compressor reported in this paper was developed by combining an inverter and a high-efficiency motor, which has a conventional 12V electrical system, a maximum power of 3kW, and a maximum speed of 90000 rpm. In addition, evaluation testing was conducted as a two-stage turbocharging system by combining it with an existing exhaust gas turbocharger. The turbocharger satisfied the specifications required by the engine, and sufficient durability was verified. The technologies being developed for mass production are also introduced in this report.

2. Characteristics of Electric Compressor

For the development of the electric compressor, the concepts below were considered for applicability to existing vehicle systems:

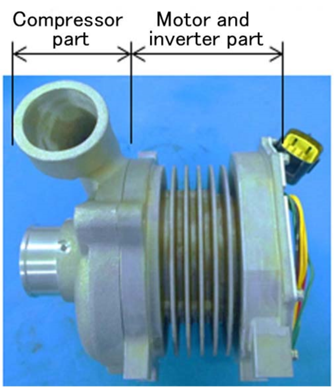
・The electrical system used is the conventional DC12V.

・The compressor, motor and inverter are integrated in one body.

*1 Chief Staff Manager, Turbocharger Engineering Department, Automotive Parts Division, Machinery, Equipment & Infrastructure
*2 Turbocharger Engineering Department, Automotive Parts Division, Machinery, Equipment & Infrastructure
*3 Manager, Turbocharger Engineering Department, Automotive Parts Division, Machinery, Equipment & Infrastructure

- A high-speed motor which allows operation at a maximum of 90000 rpm is to be developed.
- The high-speed motor generates low noise, and can start from the stopped condition.
- A separately placed fan for cooling or a cooling system is not used.

The main targets of the electric compressor developed in this study are the improvement of engine low-speed performance and turbocharging response by eliminating the turbo lag by combining the electric compressor with an existing exhaust gas turbocharger. A photograph and the specifications are shown in **Figure 1**. The electric compressor consists of the compressor part, the motor and inverter part, and the internal cartridge assembly part. The ball bearings are grease lubricated, and they support the compressor wheel and rotor of the high-speed motor. Cooling fins are provided for air cooling to control the temperature increase caused by the rise in the temperature of the motor/inverter and bearings. The electric compressor specifications are activation by a conventional 12V power source system, a maximum of motor output of 3kW, a maximum speed of 90000 rpm, and an acceleration time to maximum speed of 0.6 second.[2]



Motor max. output	3.0kW
Max. current	250Arms
Max. rotational speed	90000rpm
Response	< 0.6 s
Pressure ratio	1.6
Flow rate	< 0.1 kg/s

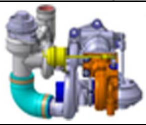
Figure 1 Photograph and specifications of electric compressor

3. Development of Two-stage Electric Turbocharging System

Improvement in fuel consumption through the supercharged downsizing of gasoline engines is progressing mainly in Europe. The improvement of combustion efficiency is necessary for further improvement in fuel consumption, and a higher supercharging pressure is required for this purpose. However, the higher supercharging pressure is subject to the constraint of the knocking limit and the reduction of exhaust gas energy. As such, a supercharging efficiency higher than the current value is required. In the development of the two-stage electric turbocharging system, an investigation was conducted for comparison with an existing two-stage turbocharging system, and its validity as a supercharging system of future gasoline engines was evaluated. **Figure 2** shows a comparison of two-stage turbocharging systems. The two-stage electric turbocharging system combining the electric compressor and an existing exhaust gas turbocharger is the most advantageous from the perspectives of low speed performance, the improvement of transient response, and the flexibility of installation.

3.1 Structure of Two-stage Electric Turbocharging System

Figure 3 shows a schematic view of the two-stage electric turbocharging system. This two-stage electric turbocharging system consists of an electric compressor, a waste gate turbocharger, a bypass valve and other components. The electric compressor developed in this study offers low noise, high efficiency and high-speed applicability through the use of a magnet motor compared with the SR (switched reluctance) motors of other companies.[3] In addition, the system is advantageous in terms of fuel consumption without electric current loss, as the compressor can start from the stopped condition during transient operation. **Table 1** shows a comparison of the advantages and disadvantages with the arrangement of the electric compressor. The advantages and disadvantages are shown depending on the electric compressor positions (layout 1 and 2), and the appropriate piping is available according to the requirements. MHI recommends layout 1, where the electric compressor is installed in the low pressure stage from the perspective of continuous operating hours and the mounting flexibility of the compressor.

	Two-stage turbocharger (Turbocharger + Turbocharger)	Mechanical super charger + Turbocharger	Electric compressor + Turbocharger
			
Steady-state performance	0	0	0
Transient performance	0	++	++
Fuel consumption	0	+	+
Back pressure	0	+	+
Mountability	0	-	+
Thermal load	0	+	+
Weight	0	-	0
Cost	0	--	-
Remarks	・Effect on catalyst temperature when engine cold starting	・Modification of clutch and engine are required	・Limit of operating time ・Flexibility of arrangement

0 : Same level as the two-stage turbocharger
+ : Better than the two-stage turbocharger
− : Worse than the two-stage turbocharger

Figure 2 Comparison of two-stage turbocharging system

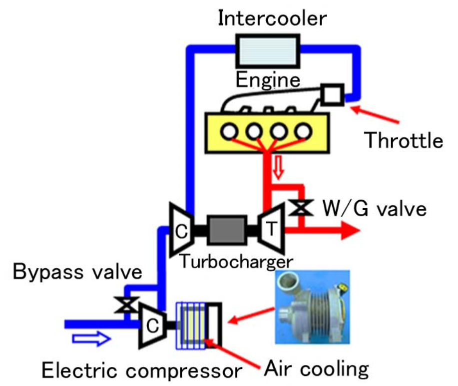
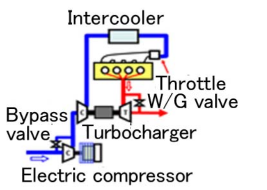
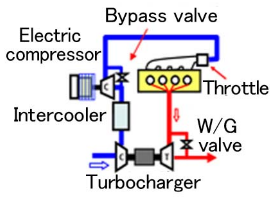
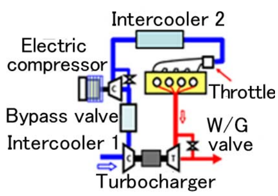


Figure 3 Schematic view of two-stage electric turbocharging system

Table 1 Comparison of advantages and disadvantages with arrangement of electric compressor

	Layout 1	Layout 2	Layout 3
Layout			
Advantages	・Improvement of mounting flexibility on vehicle ・Increase of continuous operating time	・Torque increase	・Max. torque
Disadvantages	・Slight reduction of total torque	・Decrease of continuous operating time	・Decrease of continuous operating time ・Cost increase

3.2 Reliability Evaluation of the Two-stage Electric Turbocharging System

Figure 4 shows the testing equipment on the engine. The engine used in this test is a 1.5 L gasoline engine with a maximum torque of 230 Nm and a maximum output of 113 kW. **Figure 5** shows a comparison of transient response at the engine speed of 1500 rpm. **Figure 6** shows a comparison of engine exhaust pressure in transition. The two-stage electric turbocharger improved the response by 43% compared with that of the existing two-stage turbocharger at 1500 rpm. In Figure 6, the two-stage electric turbocharger shows an improved engine exhaust pressure of 70% compared with that of the existing two-stage turbocharger. With the improvement of the engine exhaust pressure, the knock limit is improved through the reduction of gas remaining in the cylinder. This also affects the improvement of pumping loss and combustion instability. A significant engine torque increase compared with that of a waste gate turbocharger can be achieved at an equivalent exhaust pressure, and improvement in fuel consumption and drivability with ultra-high EGR can be expected. **Figure 7** shows the change of exhaust temperature increase in engine cold starting. The test duration was 500 seconds including idling for 50 seconds simulating engine cold start at the engine speed of 2000 rpm and torque of 40 Nm. From this result, the two-stage electric turbocharger shows an exhaust temperature approximately 100°C higher than that of the existing two-stage turbocharger. It was verified that the exhaust temperature could be raised rapidly in engine cold starting, and that it was effective for the activation of the catalyst. An endurance evaluation test of the electric compressor/two-stage electric turbocharging system was conducted, and the results are summarized in **Figure 8**. The endurance evaluation of the electric compressor was conducted referring to the evaluation specifications of the engine alternator and starter as the baseline. In addition, an endurance evaluation of two-stage electric turbocharging system was conducted as a system on the engine. The system met the endurance conditions for automobiles, and is currently in widespread use for evaluation testing by engine manufacturers.

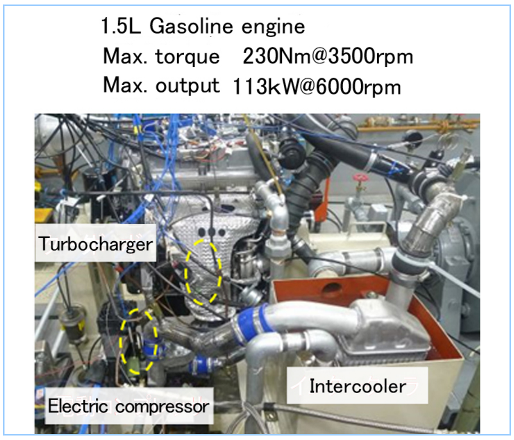


Figure 4 Testing equipment on the engine

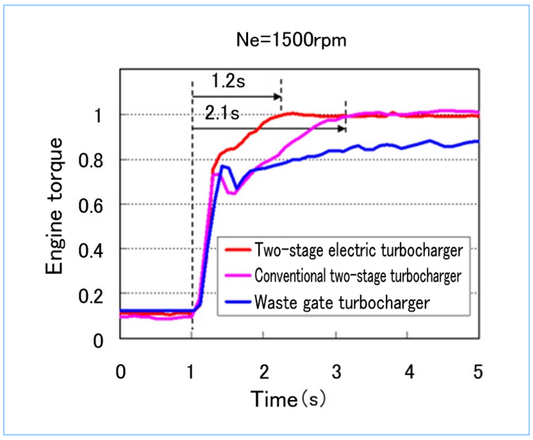


Figure 5 Comparison of transient response

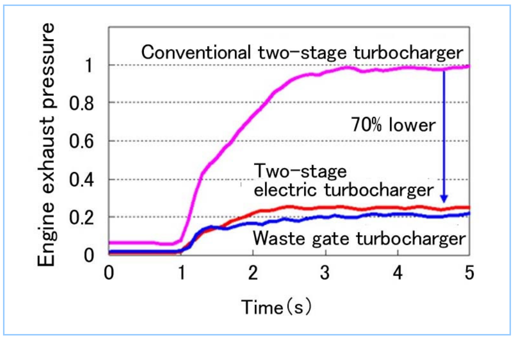


Figure 6 Comparison of engine exhaust pressure

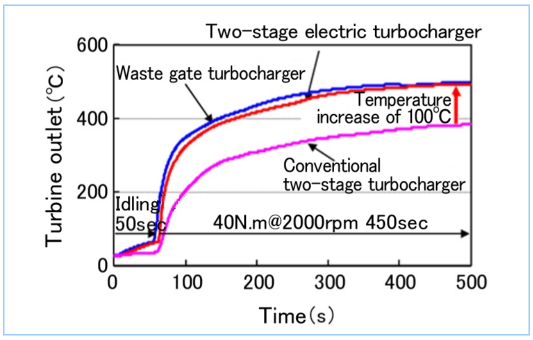


Figure 7 Comparison of exhaust temperature when engine cold starting

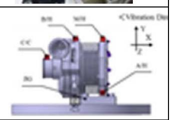
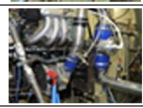
Test item	Test conditions and results	Test equipment
Rapid acceleration/ deceleration cycle endurance test	- Successful result of driving endurance mode test of passenger car	
Random cycle endurance test		
Vibration endurance test	- Operating mode : Transient - Random vibration conditions (3 directions) - Successful result of vehicle installation condition test	
Low- and high-temperature operational test	- Test temperature (low <--> high) - No problem	
Endurance test of thermal shock		
Cycle endurance test on engine test bench	- 1.5L Gasoline engine - Low speed (electricity On) <--> High speed (Off) - Successful result of endurance target	

Figure 8 Results of endurance evaluation test

3.3 Simulation Evaluation of Two-stage Electric Turbocharger

GT-Power, which is widely used as an engine simulator, was used for the comparison of the engine transient response and improvement in fuel consumption when LPL (Low Pressure Loop) EGR is introduced. In addition, a mode fuel consumption simulation was conducted with a vehicle simulation model, and the optimal control method of the two-stage electric turbocharging system was discussed. The downsizing effect of the two-stage electric turbocharger was studied with GT-Power simulation.

Figure 9 shows the engine downsizing effect. The figure shows the relation between the transient response time and engine torque of the engines with a waste gate turbocharger and the two-stage electric turbocharger. The 1.1 L gasoline engine with the two-stage electric turbocharger maintains stable performance, and improves the transient response by 42% compared with the 1.5 L gasoline engine with a waste gate turbocharger. The results verify that the two-stage electric turbocharger allows the downsizing of the engine to 1.1 L while maintaining the transient response.

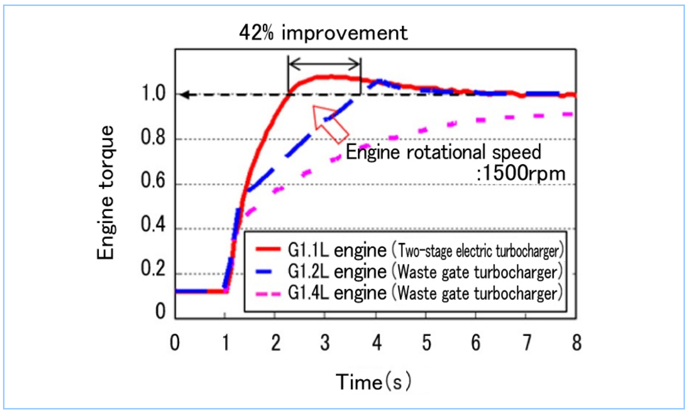


Figure 9 Engine downsizing effect (GT-Power calculation)

Figure 10 shows a comparison of transient response change by EGR. Using the 1.5 L gasoline engine with a waste gate turbocharger and no EGR as the base line, in the case of EGR at 10%, the engine torque was decreased by 19%. Contrarily, the gasoline engine with the two-stage electric turbocharger shows a 48% torque increase with no EGR, and a 17% torque increase even with EGR at 30%. These results show that the two-stage electric turbocharger allows EGR during transient operation, and significantly improves the fuel consumption while improving the transient response. Vehicle models with naturally aspirated (NA) gasoline engines, gasoline engines with a waste gate turbocharger (WG T/C), and gasoline engines with the two-stage electric turbocharger (E-2 stage) were constructed, and the fuel consumption was compared in the automobile running mode of Japanese JC08 and U.S. LA4 modes.

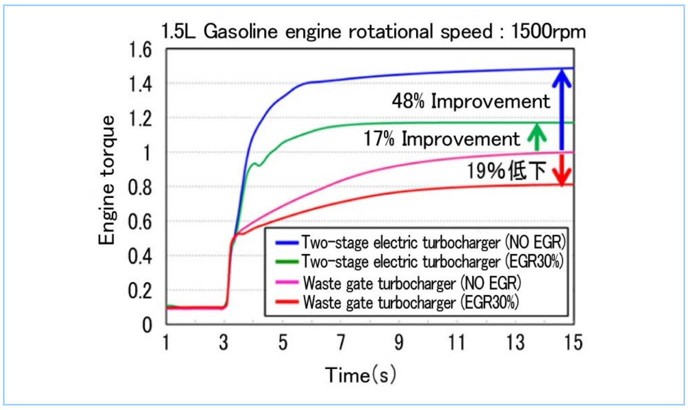


Figure 10 Comparison of transient response change through EGR (GT-Power calculation)

Figure 11 shows the results. The 1.6 L gasoline engine with a waste gate turbocharger shows an improvement in fuel consumption of approximately 10%, and the 1.2 L gasoline engine with the two-stage electric turbocharger shows an improvement of approximately 30% compared with the 2.0 L gasoline NA engine. The total displacement can be made smaller through the turbocharger downsizing effect, and the friction loss, heat loss, pumping loss and exhaust energy loss can be improved. As a result, the fuel consumption improved both in JC08 and LA4 modes. The WLTC mode planned to be adopted mainly in Europe from 2017 assumes actual driving conditions, a higher speed, and more acceleration/deceleration under a heavy load. As such, further improvement in fuel consumption can be expected.

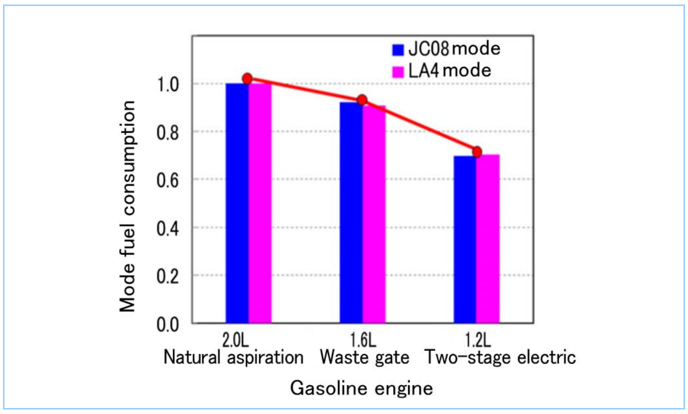


Figure 11 Fuel consumption comparison of test mode (JC08 and LA4)

4. Conclusion

A high-efficiency, high-speed motor was developed under the current 12V power source specifications. The improvement of boost pressure at an extremely low speed where the exhaust gas amount is small, and improvement in fuel consumption through the application of EGR became possible. In addition, the two-stage electric turbocharging system combined with an existing turbocharger verified further improvement in fuel consumption through a significant downsizing of the engine, as well as the improvement of drivability from the perspectives of engine evaluation testing and vehicle simulation. Moreover, the durability of the system as a two-stage electric turbocharging system was verified. The system is now expected to contribute to the expansion of business and to measures to strengthen environmental regulations through future marketing.

Reference

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2. Byeongil, A. et al., Development of Two-Stage Turbocharger System with Electric Supercharger, 2012 FISITA World Congress, F2012-A01-026.
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