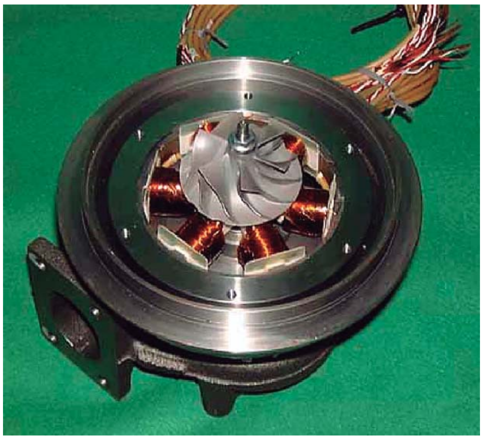

Development of the "hybrid turbo," an electrically assisted turbocharger

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If automotive engines are to achieve better environmental properties and drivability, they must be equipped with more advanced systems for operation control. Electrical operation systems are now being incorporated in engine designs for this purpose. The "hybrid turbo" is an electrically assisted turbocharger with a high-speed motor generator built in. When operating in the low-speed engine mode, the hybrid turbo can achieve better combustion, purer exhaust gas, improved torque response, and torque enhancements with motor assistance. In the high-speed engine mode, it can operate with very high efficiency by achieving regeneration of electric power in excess of the exhaust gas energy. For these reasons, the electrically assisted turbocharger is expected to be adopted as the turbocharger of the future. In recent engine tests, a new hybrid turbo developed by Mitsubishi Heavy Industries, Ltd. (MHI) has been proven to operate with improved engine torque and enhanced response compared to a conventional turbocharger. The effectiveness of this hybrid turbo has thus been confirmed.

1. Introduction

In line with efforts to conserve the global environment, regulatory authorities around the world have steadily continued to tighten their control of automobile emissions and fuel consumption. As of this writing, almost all diesel-powered vehicles are equipped with turbochargers to enhance the performance of the engines. Turbochargers are also being increasingly applied in gasoline engines as a means to downsize the engines, lighten their weights, and improve their efficiency[(1)].

Diverse engine control strategies to improve operation environments and operation performance are steadily being introduced. In response to this diversification, a new generation of VG turbochargers (Variable Geometry Turbocharger) capable of changing turbine capacities in accordance with engine loads have rapidly come into wide use[(1)]. Automakers are installing diverse electrical equipment and introducing more electronic control systems in their cars, both hybrid and conventional, and 36 V is being introduced as a battery power source. Electrical operation systems such as electronically controlled actuators are also being increasingly incorporated into turbochargers. And with progress in power electronics, automakers can now create hybrid generators by fusing turbochargers with newly developed motor generators that run at ultrahigh speeds of 100 000 rpm and over. If the adoption of 36 V for the battery power source becomes widespread, an electric load of several kWs or more can be used. Thus, the turbocharger of the future may soon be a hybrid.

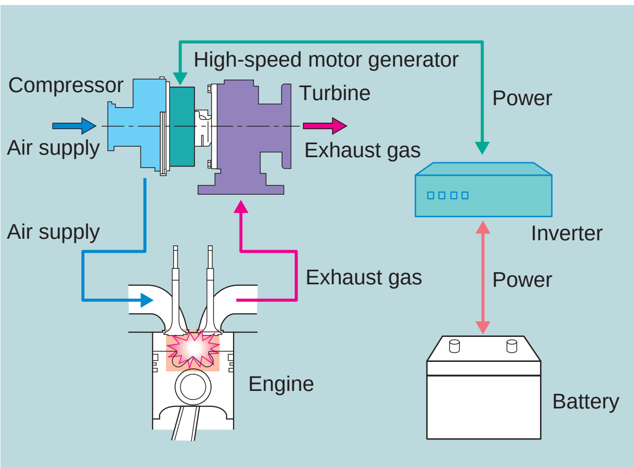

Fig. 1 System diagram of hybrid turbo
The high-speed motor generator in the hybrid turbo gives and receives electricity to and from the battery through an inverter, in accordance with the engine load.

2. Classification of electrically assisted charging systems

Two types of electrically assisted charging systems are equipped with ultrahigh-speed motor generators. The first, the "hybrid turbo," is a conventional turbocharger with a high-speed motor generator built in. **Figure 1** shows the hybrid turbo system and **Fig. 2** shows the prototype. In a conventional turbocharger, a turbine driven by the exhaust gas from the engine turns a compressor on the same shaft, supplying high-pressure air to the engine. The motor generator incorporated into this type of turbocharger assists the turbo when the engine speed is low and the exhaust gas energy is insufficient, thereby improving the transient response delay (turbo lag), the Achilles heal of the conventional turbo.

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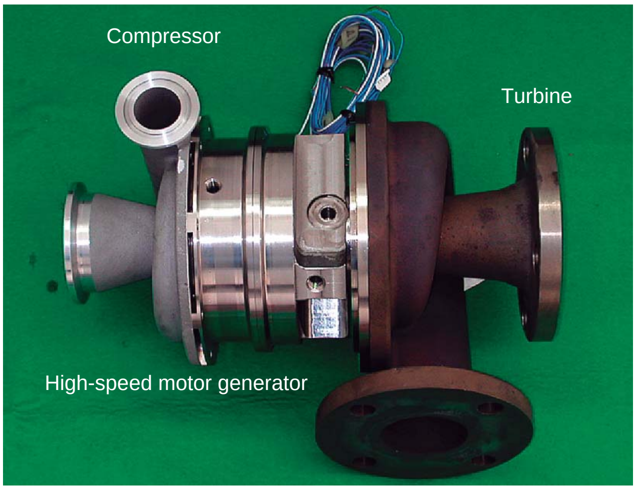

Fig. 2 Hybrid turbo
External appearance of the hybrid turbo prototype. A high-speed motor generator is incorporated between the compressor and turbine.

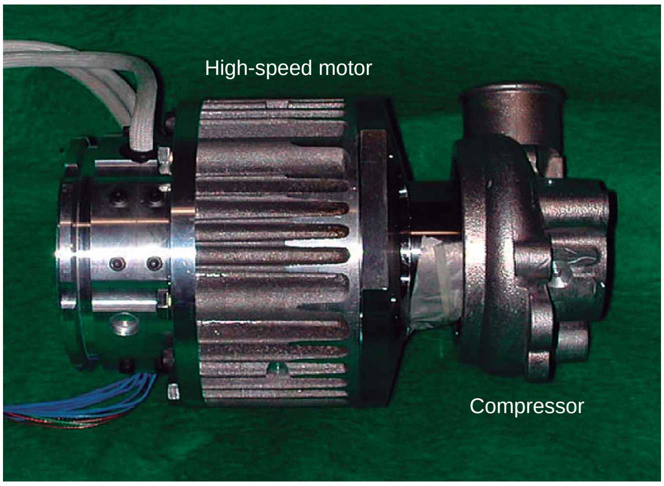

Fig. 3 Electrically operated compressor
External appearance of the electrically operated compressor prototype. The centrifugal compressor is driven by the high-speed motor.

In the high-engine speed zone, on the other hand, excess exhaust gas energy can be recovered as electric power and either stored in the battery or used to assist the engine through the ISG (Integrated Starter Generator).

The second type of electrically assisted charging system is basically a high-speed motor driving a supercharger without the use of exhaust gas. The motor torque drives the compressor used to supply high-pressure air to the engine. **Figure 3** shows a prototype of an electrically operated compressor combining a centrifugal compressor and high-speed motor(1).

3. Development of hybrid turbo

3.1 Development objectives

The development objectives for the hybrid turbo were defined through performance studies based on the engine simulation(2).

- 10 % improvement of fuel efficiency in the low-engine-speed zone
- 50 % improvement of engine torque in the low-engine-speed zone
- 70 % reduction of turbo lag during acceleration

The relationship between required motor output and engine performance was estimated in the simulated operation of a 2L diesel engine equipped with an intercooler. The motor efficiency was assumed to be 90 %, and the simulation data for the turbine and compressor were taken from data on actual operation tests.

Figure 4 shows the simulation results. Engine torque as a steady state characteristic was improved by 50 % with a 1 kW motor assist and by 100 % with a 2 kW motor assist. The results also show an 8 % improvement in fuel efficiency with the 1 kW motor assist and a 12 % improvement with 2 kW. According to the assessments of transient characteristics, the turbo lag was reduced by 50 % with a 1.3 kW motor assist and by 70 % with 2.0 kW. Based on these simulation results, the output of the prototype motor was set at 2.0 kW.

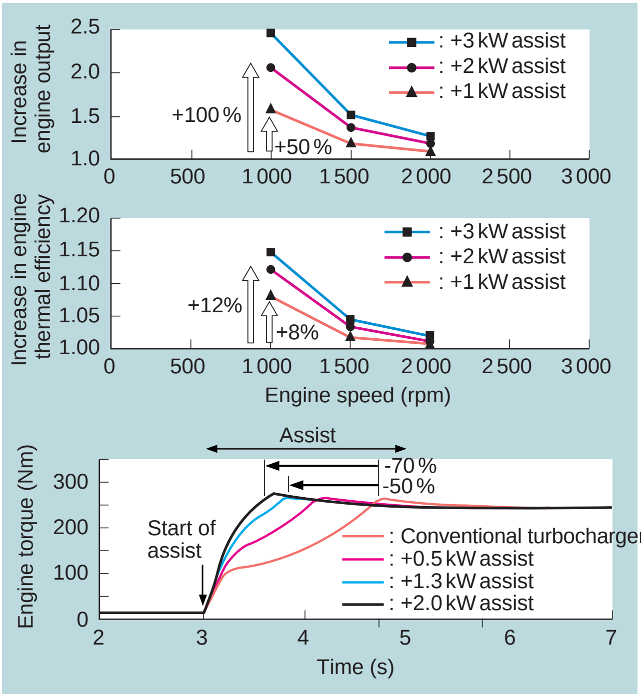

Fig. 4 Engine simulation results
The hybrid turbo enhances the torque and thermal efficiency in the low-engine-speed zone and improves the overall response.

3.2 Structure and characteristics

The prototype hybrid turbo was structured with a high-speed motor generator placed between the compressor and turbine. With the motor generator incorporated into the hybrid turbo, increases in the shaft length and outside diameter were inevitable. Fortunately, these increases could be minimized by carefully designing the shapes and positioning of the bearing, magnet rotor (rotor), and stator to keep the engine installation space equivalent to that in the conventional turbochargers. Reliability and reduced cost were secured by incorporating the same turbine and compressor used in conventional turbochargers, as well as other conventional turbocharger parts with proven performance.

The magnet rotor of the motor generator is positioned in the overhang shaft system in the back surface of the compressor, and the critical speed of the shaft system has been reduced compared with that in conventional turbochargers. To accommodate this design we adopted a full float bearing, a component proven to be highly effective for restraining shaft vibrations at high-speed rotations in conventional turbochargers, and we held down the resonance magnification by tuning the bearing gaps, etc. A rotor vibration analysis and verification test confirmed that this design was free of problems.

3.3 Power electronics

3.3.1 Ultrahigh-speed motor generator

A permanent magnet synchronous type was adopted as the ultrahigh-speed motor generator. The rotor magnet and stator were reduced in size by incorporating a neodymium rare-earth magnet with strong magnetism and relying on concentration winding, a winding method that can be used to reduce the size of the winding wire end. By keeping a relatively large gap between the rotor and stator, we managed to reduce the inductance which disturb the rapid change of current. Carbon fiber reinforcement was used to retain the magnet against the centrifugal force of the rotor, fulfilling a crucial design requirement for the ultrahigh-speed motor generator.

If the motor generator is downsized, the density of the heat generation rises sharply due to motor loss and hinders the cooling. When cooling is insufficient, excessive rise in the winding wire temperature and rotor magnet temperature cause a deterioration of insulation performance and irreversible demagnetization respectively. Another factor that cannot be ignored in motor generators is loss of the eddy current in the rotor. This is an especially important factor in the ultrahigh-speed motor generator and must be reduced by any means necessary. Based on the results of the magnetic field analysis, we found that a 6-slot structure for the stator could reduce the rotor eddy current loss in our prototype(2)(3). We also improved the cooling system with the use of forced oil cooling for the stator and forced air cooling for the rotor. **Figure 5** shows the external appearance of the prototype and stator.

3.3.2 Inverter

The voltage-source PWM (Pulse Width Modulation) inverter is widely used as an inverter to drive permanent magnet motor generators. However, in this high-speed application, the fundamental electric frequency reaches several kHz. Therefore it is difficult to form good sinusoidal current waveforms using the voltage-source PWM. As an alternative, we adopted a pseudo-current source inverter in the prototype(2)(3). This approach is favorable for the control of ultrahigh-speed motors as it enables the straightforward control of the current values and phase. The inverter circuit is made up of a buck-boost chopper that controls current values and a 6-step inverter circuit that controls the current phase. Switching between buck and boost voltage in the buck-boost chopper makes it possible to operate the inverter in two directions: motoring and regeneration. We also managed to omit the use of external position detectors such as the hall element and resolver, as the magnet rotor rotation position required for stable torque generation is detected based on the waveform of the induced voltage generated in the stator. We are forced to rely on the open loop for control, however, as the induced voltage is small and difficult to detect during startup and at extremely-low speeds.

To power the inverter, we expect to use 12 V in the battery for general passenger cars, 24 V for commercial vehicles, and 36 V for future applications. For the prototype, however, our chief concern was to confirm the performance and effectiveness of the hybrid turbo itself. Thus, we initially set the voltage as high as 72 V and used integral multiples of the voltage in the existing batteries.

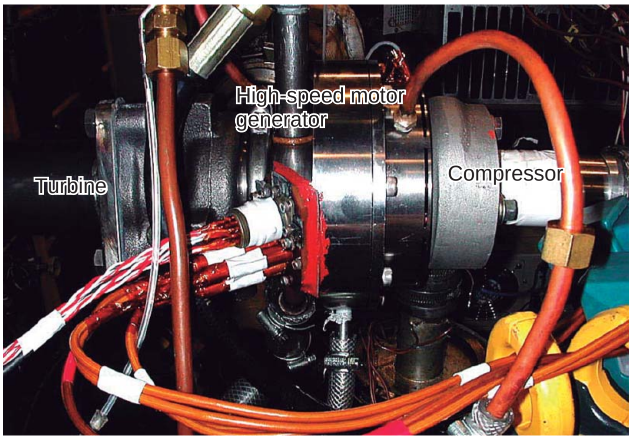

Fig. 5 Conditions of the test on the hybrid turbo, and the external appearance of the motor stator
Hybrid turbo during the engine testing. A 6-slot concentration winding method is adopted for the motor stator to downsize the component and reduce loss.

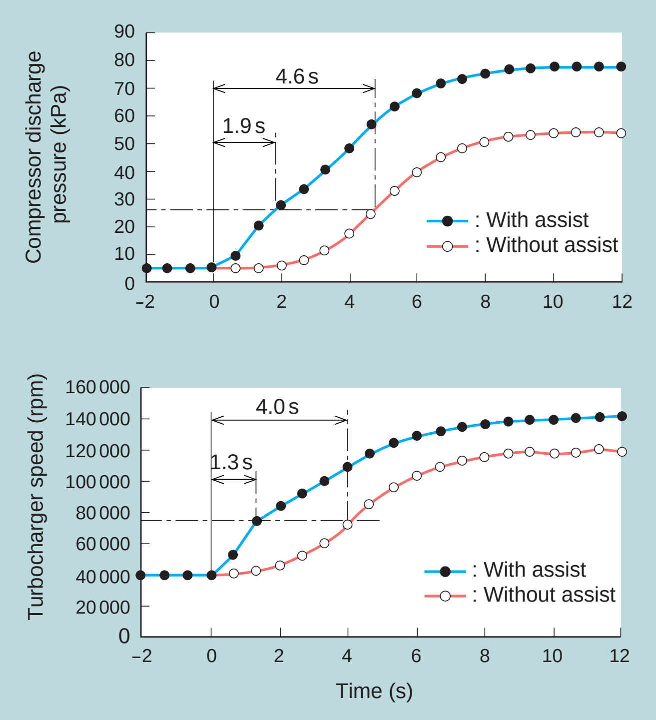

Fig. 6 Comparison of the transient response of the turbocharger speed and discharge pressure ratio with the motor assist and without motor assist
The motor assist greatly shortens the start-up times for the turbocharger speed and compressor discharge pressure.

Table 1 Comparison between the turbocharger speed and discharge pressure ratio before the motor assist and after the motor assist

Turbocharger speed (rpm)	Before assist	40 000	81 000	100 000	122 000
	After assist	85 000	109 000	121 000	138 000
Compressor discharge pressure ratio	Before assist	1.05	1.21	1.33	1.50
	After assist	1.23	1.41	1.51	1.66

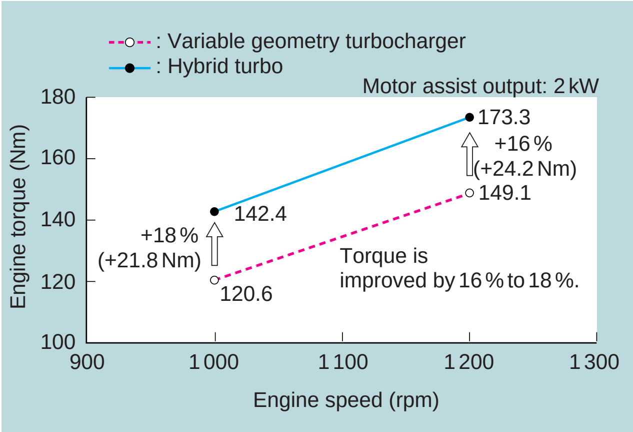

Fig. 7 Comparison of the steady torque of the engine between the hybrid turbo and variable geometry turbocharger
Torque is improved by 16 % to 18 % at low engine speeds with the motor assist.

3.4 Test results

3.4.1 Unit test results

We tested the hybrid turbo prototype by a unit test to confirm the basic performance(2). The test was conducted on a test bench for the turbocharger and an air source was used to drive the turbine. A 72-V DC stabilized power-supply was used to power the inverter over a long period of stable operation and measurement.

Table 1 shows a comparison of the rotational speed of the turbocharger and the compressor discharge pressure ratio in the prototype before and after motor assist. The motor was controlled to a constant torque of 0.16 Nm throughout the test (equivalent to 120 000 rpm, 2 kW).

Figure 6 compares the transient response of the turbocharger speed and the discharge pressure ratio with and without motor assist. The effects of the motor assist are noticeable if we look at the values during acceleration: the turbocharger took 33 % less time to reach 74 000 rpm and the compressor discharge pressure took 41 % less time to reach 26 kPa with the motor assist. The turbine torque became dominant after several seconds of acceleration, leaving the steady differences shown in Table 1.

3.4.2 Engine test results

The hybrid turbo was also tested by an engine combination test on the test bench(2) using a 2L-class direct-injection diesel engine equipped with an intercooler. This type of engine usually incorporates the variable geometry turbocharger. During the testing, the hybrid turbo was controlled to a constant torque of 0.16 Nm at 120 000 rpm or less and to a constant output of 2.0 kW at 120 000 rpm or more.

Figure 7 compares the steady torque of the engine with the hybrid turbo used and with the variable geometry turbocharger used. The steady torque of the engine improved by about 17 % at engine speeds of 1000 rpm and 1200 rpm. This effect was thought to be due mainly to the higher air-fuel ratio.

Figure 8 compares the transient response of the turbocharger speed with the hybrid turbo and with the variable geometry turbocharger. The engine begins in a high-idle condition, and the engine output and output of the hybrid turbo motor both increase as the engine load increases. The turbocharger speed accelerated more quickly with the use of the hybrid turbo than with the variable geometry turbocharger. The overall acceleration performance with the hybrid turbo was also confirmed to be equal to or better than that with the variable geometry turbocharger.

4. Challenges and outlook for the future

We have experimentally confirmed that the hybrid turbo effectively improves engine torque and eliminates turbo lags when applied to automotive engines. In the future we will work on the following tasks toward the development of an in-vehicle hybrid turbo.

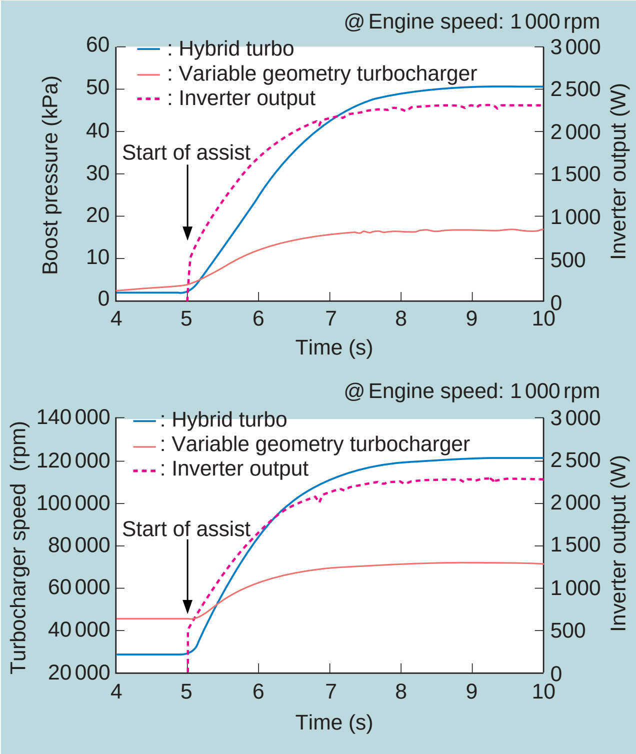

Fig. 8 Comparison between the transient response of the turbocharger speed and boost pressure with the use of the hybrid turbo and with the use of the variable geometry turbocharger
The hybrid turbo has a transient performance equal to or better than that of the variable geometry turbocharger.

- Establish a technology for ultrahigh-speed motors and inverters that can be realized electrically and thermally based on the specifications for the existing in-vehicle 12-V and 24-V batteries, or for the 36-V batteries expected to be widely adopted in the future
- Establish a method to control the hybrid turbo as part of an optimum system in combination with an engine and exhaust gas aftertreatment device
- Establish a power supply system comprised of the hybrid turbo working effectively with other in-vehicle electric components

5. Conclusion

To help us adapt to the ever control of automobile emissions and fuel consumption in today's regulatory environment, our group has tested and confirmed the effectiveness of the prototype of a hybrid turbo expected to be adopted as a new technology for turbochargers. In addition to the hybrid turbo itself, we are also developing an electrically operated supercharger and an electrically operated compressor for fuel cells based on the application of the electrically operated supercharger, as products to which we can apply an ultrahigh-speed motor generator[1]. Henceforth we hope to use our turbocharger and ultrahigh-speed motor drive technologies to further improve the environmental performance of cars and enhance the pleasure of driving.

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