Trend of Turbocharging Technologies

Review

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Abstract

Nowadays, much greater emphasis is being placed on improving the fuel consumption of automobiles due to the global move to reduce CO_2 emissions. Ideally, an engine should be able to simultaneously offer a high power density and low fuel consumption. High-pressure turbocharging is indispensable to improving the fuel consumption of an engine by enabling downsizing and lean-boost. To this end, there is a demand for a turbocharger with a wide flow range. The characteristics of different turbocharging systems have been evaluated by one-dimensional engine performance simulation. The variable-geometry turbochargers with motor assist are effective at improving the low-speed torque and the transient response of an engine. On the other hand, the surge limit of the compressor restricts the charging pressure at low engine speeds. A key technology for improving the surge limit involves the development of a casing treatment and a variable-geometry compressor. A two-stage turbocharging system offers the double advantage of eliminating the surge limit and improving the transient response. Unsurprisingly, however, the engine system and its control become more complicated. Therefore, it is vital that we develop an optimum turbocharging system to suit the engine specification.

Keywords: Turbocharged engine, Turbocharger, Simulation, Motor, Compressor, Turbine, Variable nozzle, Variable inlet guide vane, Surge

1. Introduction

The introduction of measures to reduce CO_2 emissions in Europe has led to the aggressive pursuit of downsizing and reduced fuel consumption, based on high-pressure turbocharging technology.[1, 2] An additional benefit of this avenue of research is that the improved low-end torque and better engine response produce a product that is more appealing to buyers of passenger cars. The goals that a turbocharger must satisfy are the ability to provide high-pressure turbocharging at low engine speeds, a high transient response, and high efficiency at a high pressure ratio. Different turbocharger designs such as the variable geometry turbocharger, electrically assisted turbocharger, and two-stage turbocharger have been developed as a means of achieving the above-mentioned performance improvements. Also, the Variable-Nozzle Turbocharger (VNT), which is capable of changing the flow capacity of the turbine, is already in widespread use in diesel passenger cars. The electrically assisted turbocharger improves the transient response and, because it is excellent at achieving high-pressure turbocharging at low speeds, manufacturers are putting considerable effort into its development.

Immediately after the gas turbine was first proposed by Dr. Alfred J. Buchi of Switzerland in 1912, Dr. Sanford A. Moss of the United States devised the concept of the turbocharger. The 1930s saw the first practical application of the technology, when it was applied to large-scale diesel engines for land-based and marine installations. In 1938, it was applied to an aircraft engine (Boeing B-17), which was required to fly at high altitudes. After the 1960s, automotive applications of turbochargers became widespread. Turbocharging is now indispensable for engines that must offer high power densities, as well as for low-emission diesel engines. Moreover, turbocharging is seen as a means of reducing fuel consumption by enabling downsizing and lean-boost for direct-injection gasoline engines.

2. Trends in turbocharged engine technologies

Among the various engine superchargers that have been commercialized, there are turbo types such as the turbocharger and also positive displacement types such as the roots blower and rotary screw compressor. The main advantages of the turbocharger are its small size and large flow capacity. It also has the capacity to reduce fuel consumption due to the fact that waste heat is recovered by the exhaust gas turbine. An inherent disadvantage with the turbocharger, however, is that it cannot produce sufficient charging pressure at low engine speeds when there is little energy in the exhaust. Positive-displacement types, on the other hand, can produce sufficient charging pressure at low speeds. They do not reduce the fuel consumption, however, as they are driven by the engine crankshaft. Therefore, a universal goal of manufacturers is the development of an automotive charging system that can produce sufficient charging pressures over the entire operating range of the engine. Nowadays, engine downsizing has become an important technology, especially for passenger cars, given the need to reduce CO_2 emissions and downsize the amount of space taken up by the engine compartment. Several European and Japanese manufacturers are also pursuing the development of turbocharging systems that can produce high charging pressures at low speeds through the use of variable-geometry turbochargers, motor-assist turbochargers (MATs), and two-stage turbochargers.[3]

Figure 1 shows the trend in the specific power of diesel engines in Europe. By 2010, the goal is to develop a high specific power engine capable of producing 70 kW/L by means of high-pressure turbocharging with a VNT, variable-geometry compressor, or MAT. The main reason for this is the need to reduce the amount of CO_2 emissions to 115 g/km by downsizing of the engine, as shown in **Fig. 2**. A

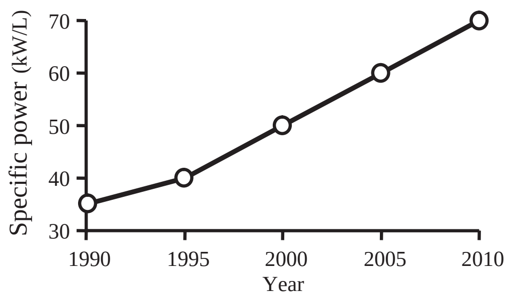

Fig. 1 Trend of the engine specific power.

similar approach is being taken for gasoline engines, and we have already seen excellent progress in the research and development aimed at eliminating or controlling the knock that has been a serious problem with high-pressure turbocharging. **Figure 3** shows the technologies used for improving the low-end torque of a turbocharged engine, together with a schematic of the system. Turbocharged engines with a conventional turbocharger offer less torque at low speeds than other turbocharging systems, given that the turbocharger characteristics are optimized for high engine speeds. Accordingly, the transient response is lower than that of other turbocharging systems. On the other hand, it offers a higher turbine inlet pressure which leads to increased fuel consumption if the turbocharger characteristics are optimized for low engine speeds. For a turbocharged engine with the VNT, as is widely used in diesel engines, the boost pressure can be raised by controlling the VN at low engine speeds. However, the amount by which the pressure can be increased at low engine speeds is limited due to the low exhaust energy, such that engine back pressure arises. The MAT, however, is able to raise the boost pressure at low engine speeds. So, by adding motor assistance, we should be able to attain torque characteristics on a par with a large-displacement engine. A MAT can also recover thermal exhaust energy by acting as a dynamo at high engine speeds. As a result of this, we can expect a significant improvement in fuel consumption.

3. Trends in turbocharger technologies

3. 1 Key technologies of advanced turbochargers

The turbochargers used in passenger cars must be able to produce a wide flow range and a high transient response. **Figure 4** shows the compressor performance, together with the key technologies demanded of a turbocharger. To obtain a high boost pressure over the wide operating range of a turbocharged engine, the turbocharger has to operate at a high pressure ratio and high rotational speed over a wide flow range. On the other hand, the compressor has a surge limit that is related to the flow rate and therefore cannot be operated at flow rates less than the surge limit. Otherwise, the flow becomes unstable and periodic pressure fluctuations characterized by loud noise tend to occur. To overcome this, the rotational speed of the turbocharger has to be increased by controlling the variable nozzle vane angle or the power of the motor assistance, while shifting the surge limit of the compressor towards a lower flow rate, or eliminating it altogether, in order to increase the boost pressure at low engine speeds. There are two ways of

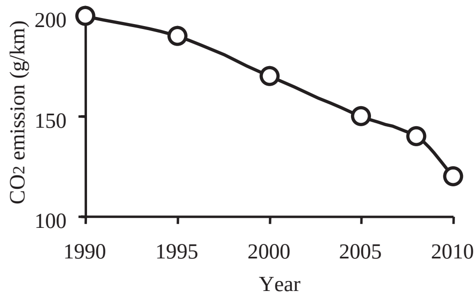

Fig. 2 Trend of the CO_2 emission.

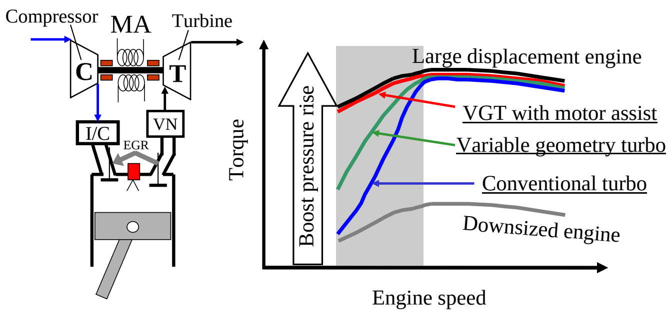

Fig. 3 The means of the low-end torque improvement.

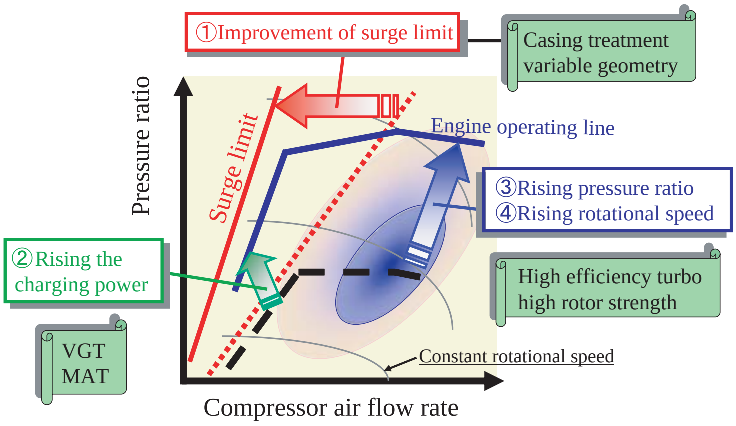

Fig. 4 Turbocharger technologies for high pressure charging.

eliminating the surge limit. The first is the application of two-stage turbocharging whereby the small compressor of the high-pressure turbocharger is used at low engine speeds. Unfortunately, a disadvantage of two-stage turbocharging is that the system is more complex and larger than single-stage turbocharging. The second method involves bypassing the compressor discharge air to the compressor inlet so as to increase the flow rate of the compressor. This, however, causes an increase in the turbine inlet pressure due to the increase in the compressor power. As a result, the fuel consumption of the engine deteriorates. Therefore, a means of improving the surge limit of the compressor is an essential technology. There are several means of improving the surge limit of a centrifugal compressor. One effective means is to re-circulate part of the air that is compressed by the impeller to the impeller inlet by using a casing treatment on the shroud wall.[4] Also, controlling the Variable Inlet Guide Vane (VIGV) or the variable diffuser vane of the compressor is an effective means of improving the surge limit. Manufacturers around the world are currently working hard on developing these technologies. Furthermore, it is necessary to widen the variable flow range of a variable-geometry turbine for both gasoline and diesel engines in order to improve the low-end torque. In addition, improving the turbocharger efficiency in the region where the pressure ratio is high is important to reducing the turbine inlet pressure for high-pressure turbocharging. A high turbine inlet pressure causes an increase in the fuel consumption, especially in the case of gasoline engines, due to the knock phenomenon.

3. 2 Trends in turbocharger development

Figure 5 shows one example of a VNT that was developed for use in diesel engines. The VNT has rapidly gained popularity in Japan and Europe despite its higher cost because it offers the advantages of low-end torque, transient response, and lower turbine inlet pressures at high speeds, relative to conventional turbochargers. At present, the VNT is the only technology available that allows diesel engines to satisfy current emissions regulations. On the other hand, the VNT is not compatible with the high gas temperatures of gasoline engines because of its complicated structure and links.

Figure 6 shows a schematic of a MAT. The high-speed motor has its permanent magnet installed on the shaft of the rotor while the stator is in the bearing housing. Because the motor is sensitive to heat, the cooling method was an important aspect of the development. Moreover, the outer diameter of the permanent magnet cannot be made much bigger than it already is because the combined strength of the permanent magnet and the shaft is low. To increase the power of the motor, therefore, the length of the permanent magnet has to be extended. Unfortunately, this leads to a reduction in the critical speed of the rotor shaft, vibration, and a risk of damage when operating at high speeds.

Because the surge phenomenon of the compressor sometimes leads to damage to the rotor, it has been the subject of research for some time and by many different manufacturers. Many kinds of casing treatments have been investigated to improve the surge characteristic and have been put

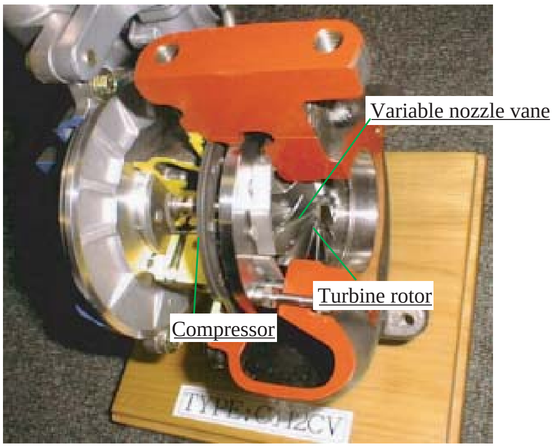

Fig. 5 Picture of the VNT.

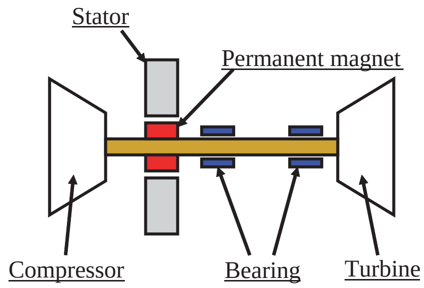

Fig. 6 Structure of the MAT.

commercialized in large-scale turbochargers. Moreover, the surge flow rate can be reduced by using a compressor with a VIGV or a variable diffuser. A VIGV installed upstream from the impeller inlet can control the velocity angle of the flow at the impeller inlet, so that the flow characteristics of the compressor can be controlled. A variable diffuser installed downstream from the impeller exit can control the flow through the diffuser where the velocity is higher than at the impeller inlet. So, the changes in the flow characteristics with the diffuser vane angle are very sensitive compared with the VIGV. And, the performance of the compressor with the variable diffuser is highly dependent on the clearances between the stationary side walls and the variable diffuser vanes. A compressor with a variable diffuser has a higher efficiency at low flow rates and a lower efficiency at high flow rates than a conventional compressor. On the other hand, a compressor with a VIGV has a slightly higher efficiency in the low- to medium-flow regions and similar efficiency at a high flow rate, relative to a conventional compressor.

4. Evaluation of turbocharging systems

The role of turbocharging is to obtain the charging pressure demanded by the engine at as low a turbine inlet pressure as possible. To this end, it is necessary to use the optimum turbocharger system. In addition, the technology for matching the turbocharging system with the engine is also important. Therefore, the characteristics of some kinds of high-pressure turbocharging systems were studied by means of simulation to clarify the advantages and drawbacks of the system.

4. 1 Steady state characteristics

We examined turbocharging systems that can produce a high boost pressure over the entire operating range. These are shown in **Fig. 7**. We assumed the use of a high-pressure turbocharged engine for which the boost pressure could not be obtained by using a conventional system. The target boost pressure was almost 300 kPa across the entire operating range, and the engine displacement was 2000 cc.

We first looked at a VNT turbocharging system with and without motor assist. Figure 7 shows the boost pressure obtained with each system and the power of the motor assist. The target boost pressure cannot be obtained at low engine speeds when using a VNT single-stage turbocharging system without motor assist, even if the variable nozzle is fully closed. If the maximum 5.6 kW of motor assist is applied to the VNT, however, the targeted boost pressure can be achieved, as shown in Fig. 7. It is generally believed that the development of a turbocharger with 5.6 kW of motor assist is technically very difficult, as mentioned in **Sec. 3.2**.

Figure 8 shows the operation plot for the compressor on a performance map. The majority of the operation plots are in the flow-rate region below the surge limit. So, it is necessary to significantly

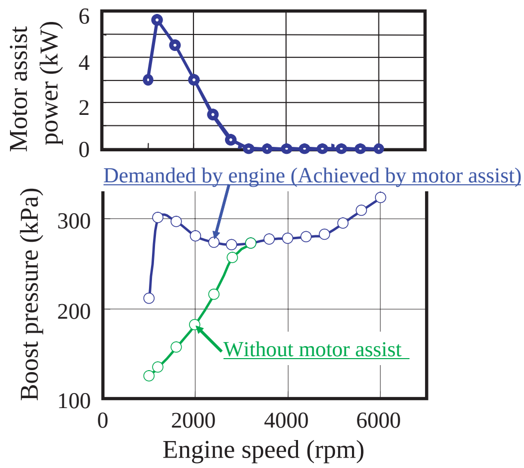

Fig. 7 Demanded boost pressure of the engine evaluated.

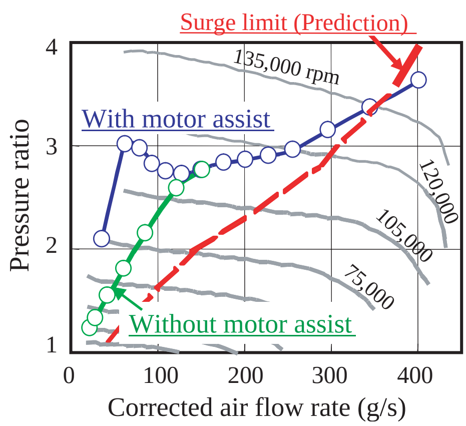

Fig. 8 Compressor operation lines on its performance map (single-stage).

improve the surge limit of the compressor at the same time as developing a high-power MAT so as to achieve the target boost pressure. We believe that a non-surge compressor can be developed by using variable-geometry devices together with a casing treatment. **Figure 9** shows the circumferential velocity of the impeller exit. The velocity reaches 600 m/s at high engine speeds, which is incompatible with current aluminum alloy impellers because this would over-stress the impeller. It would be necessary, therefore, to use a high-strength material such as titanium to achieve the required strength. The stress in the impeller can also be lessened by reducing the backward angle of the impeller. On the other hand, it is necessary to further improve the surge limit because the surge limit deteriorates when the backward angle is reduced. Moreover, the heat-resistance of the compressor exit piping has to be improved because the temperature of the compressor discharge air reaches 523 K, as shown in **Fig. 10**.

Next, we examined a two-stage turbocharging system with two VNTs. **Figure 11** is a schematic of the system, together with a performance map showing the operation plots for each compressor. The variable nozzles were controlled so as to raise the rotational speed of the small turbocharger for the high pressure stage at low engine speeds. Then, they were controlled so as to raise the large turbocharger's speed at high engine speeds. The two-stage turbocharging system also needs motor assist to obtain the target boost pressure. However, the motor assist power of 3 kW is less than that of the single-stage turbocharging system, as shown in **Fig. 12**. Furthermore, the target boost pressure at low engine speeds can be obtained by slightly improving the surge limit of the conventional compressor. In addition, the problem of the strength of the aluminum alloy impeller is avoided because the pressure ratio of each individual compressor is lower than that of the single-stage system. However, the turbine inlet pressure in the high-pressure stage produces a high value at high engine speeds because the flow capacity of the small compressor is too low. It is thought that the turbine inlet pressure can be reduced by bypassing the small compressor at high

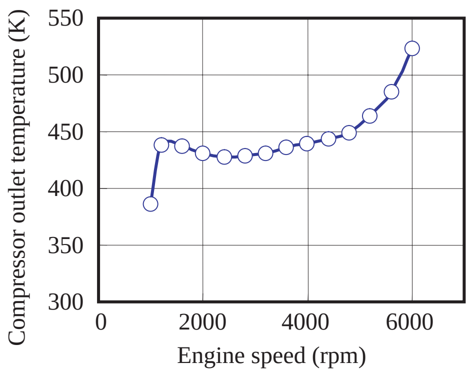

Fig. 10 Compressor outlet temperature (single-stage).

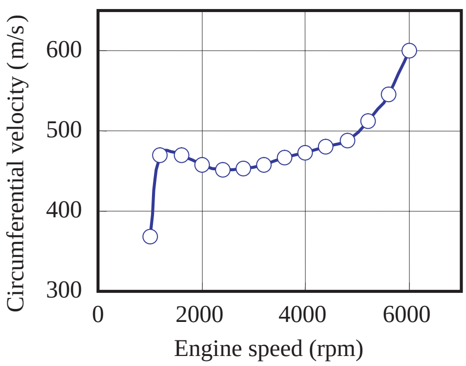

Fig. 9 Circumferential velocity of the impeller exit (single-stage).

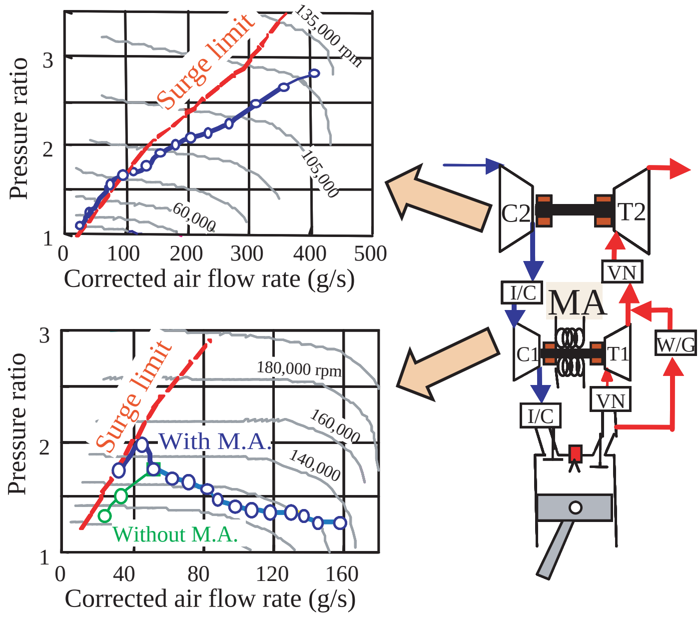

Fig. 11 Compressor operation lines on its performance map (two-stage).

engine speeds. Unfortunately, the structure of the system and its control are much more complex. **Figure 13** shows the turbine inlet pressures, that is, the engine back pressures of both the two-stage and single-stage systems. The engine back pressure becomes high at high engine speeds because the efficiency of current turbochargers falls at high pressure ratios. For our calculations, we assumed a turbine outlet pressure of 45 kPa at high engine speeds. The engine back pressure is equal to the value of the turbine outlet pressure multiplied by the turbine pressure ratio. Therefore reducing the pressure loss through the exhaust piping significantly reduces the engine back pressure. So we believe that technologies for both reducing the pressure loss in the exhaust piping and improving the turbocharger efficiency are vital to high-pressure turbocharged engines.

4. 2 Transient characteristics

We examined the effect of the motor assist power on the transient response of a turbocharging system. **Figure 14** shows the time-dependent change in the engine speed that we assumed. We considered a single-stage turbocharging system with a VNT, keeping the VNT vane position constant. **Figure 15** shows the increase in the time-dependent boost pressure when the motor assist power is added to the VNT (upper part of the figure). Under these operating conditions, the time needed to reach the same boost pressure can be significantly shortened by adding about 1.5 kW of motor assist power. When 3 kW of motor assist is added, the boost pressure momentarily overshoots the final pressure. Thus, the motor assist produces a significant improvement in the transient response of a turbocharged engine. It is necessary, however, to carefully control the amount of motor assist.

5. Summary

A universal trend in engine technology is

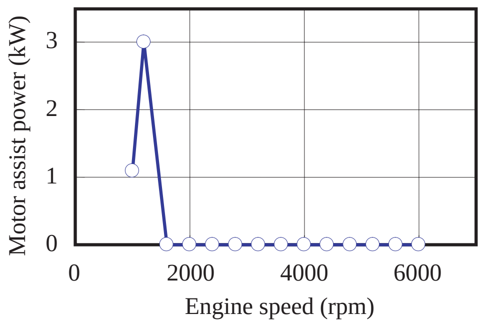

Fig. 12 Motor assist power (two-stage).

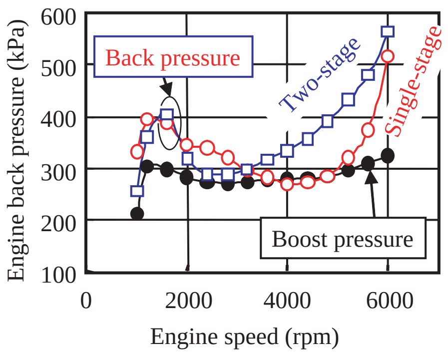

Fig. 13 Comparison of engine back pressure between single-stage and two-stage.

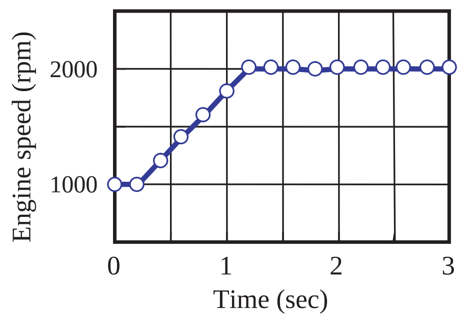

Fig. 14 Time dependent engine speed for transient calculation.

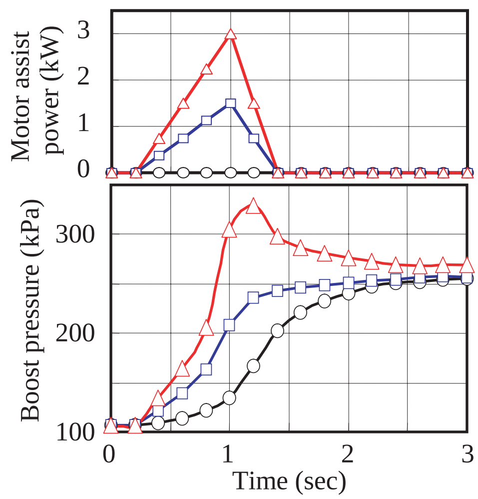

Fig. 15 Effect of the motor assist power on the transient response.

downsizing with high power density and lean-boosting for reducing the fuel consumption. As part of this, developers have been striving to increase the air mass flow rate. As a means of achieving this in a racing car, for example, it is possible to increase the engine speed and the boost pressure by using a turbocharger or a supercharger. It is thought that increasing the boost pressure has a positive effect on fuel consumption. And, recently, the trend has been towards much higher air mass flow rates to achieve both lean-boost and a high power density.

MATs offer the possibility of resolving the problems of insufficient low-end torque and the low transient response that are the weak points of a turbocharged engine. Furthermore, energy remaining in the exhaust gas can be recovered by adding a generator device to the MAT. This produces a significant improvement in fuel consumption. It seems clear, therefore, that in the future the individual development of engines and turbochargers will be supplanted by the development of turbocharged engine systems. Turbocharged engines incorporating new technologies are expected to make a major contribution to satisfying the demands for reduced CO_2 and NOx emissions.

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