CHAPTER 2

SUPERCHARGER AND TURBOCHARGER

2.1 MECHANICAL SUPERCHARGING

Superchargers are the main category of forced induction systems. Superchargers are compressors that are driven by mechanical means. Typically, they are driven by the crankshaft of an engine with the help of belts and pulleys. They are coupled directly to the engine and this does not allow for any delay to exist between the engine and the compressor. Superchargers are classified into two categories such as positive displacement pumps (Eg. Lysholm, Roots, Eaton, Scroll, Vane) and rotodynamic pumps (Eg. Centrifugal).

2.1.1 Positive Displacement Type

Mechanical supercharging is probably the oldest way of boosting the IC engine [Ainsdale, 1980]. Positive displacement supercharger is simpler in construction. They are easy to install and doesn’t require complicated controls in most cases. It draws power through mechanical connection to the crankshaft, and its revolution (rotational speed) is directly proportional to the speed of the engine. The engine-compressor matching is relatively easy, and the boost pressure is almost constant over the entire range of engine operating speeds. Therefore, the torque curve is flat, and the turbo-lag problem is completely overcome. In effect, a supercharged engine behaves as a naturally aspirated engine with a larger displacement volume. It is this linearity that makes designing and predicting its boosting characteristics relatively easier than turbo charging. However, a supercharged engine consumes more fuel than a turbocharged engine with comparable power since the supercharger draws power directly from the engine crankshaft.

A supercharger has two rotors, a male and a female, forming a set of chambers between themselves and the housing. The chamber’s volume is changing during the rotation and thus compresses the air internally. Since the power needed to drive the supercharger is taken directly from the crankshaft, most development work has been invested to increase the efficiency and to minimize the parasitic losses when the supercharger is not needed (i.e. part load of the engine).

The most common types of the supercharger in the market today are the Lysholm compressor and the Roots blower. Figure 2.1 & 2.2 shows the cut-away view of the Lysholm screw and roots type supercharger [Heinz, 1995]. Both are displacement pumps and from a first glance they look very similar. They differ on one big point; the Lysholm screw has internal compression while the Roots do not have internal combustion. The Lysholm Compressor works with internal compression.

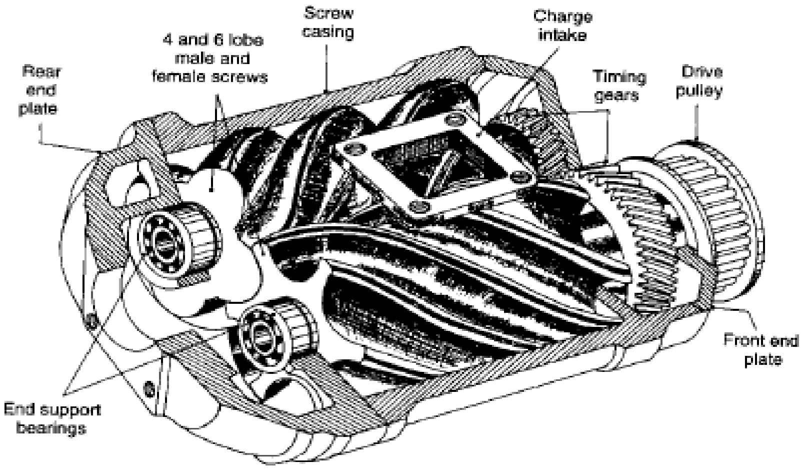

Figure 2.1 Cut-way view of the Lysholm screw supercharger [Heinz, 1995].

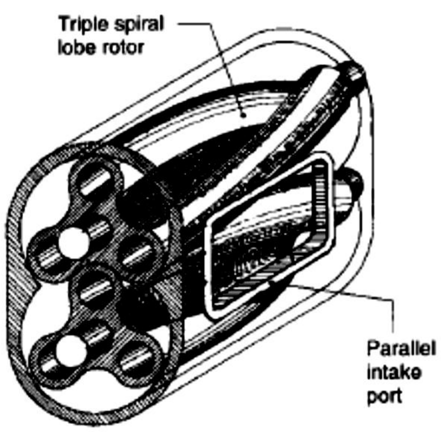

Figure 2.2 Cut- way view of the roots type supercharger [Heinz, 1995].

The Roots on the other hand works without internal compression, the compression takes place as the air is discharged from the blower outlet instead of inside the supercharger. This means that the compression takes place at isochoric conditions (i.e. constant volume). This process is known to be more power consuming and heat producing than the adiabatic process.

2.1.2 Centrifugal Compressor as a Supercharger

The centrifugal compressor has an isentropic efficiency that can match, and sometimes exceed, the efficiency of a Lysholm screw compressor. It is a dynamic machine where the rotor increases the internal energy of the air, both through increased density and increased velocity. The velocity is then carefully diffused to recover the kinetic energy as static pressure. Consequently, the centrifugal compressor has internal compression. Figure 2.3 shows the cut-away view of the centrifugal supercharger.

Unfortunately, the flow vs. speed characteristics of the centrifugal compressor is very non-linear. A fixed gear ratio between the compressor and the crankshaft results in a very peaky boost pressure delivery. Despite this, it has been used in cars, during the 1930s and 1950s. The speed of the centrifugal compressor is above 100000rpm and it is up to 10 times higher than roots and about 3 to 5 times the speed of a screw compressor. The need for a gearbox caused trouble for the designer. High speeds can lead to both sound problems if gears are used and the torque needed for acceleration can be rather high even if the moment of inertia is not particularly high.

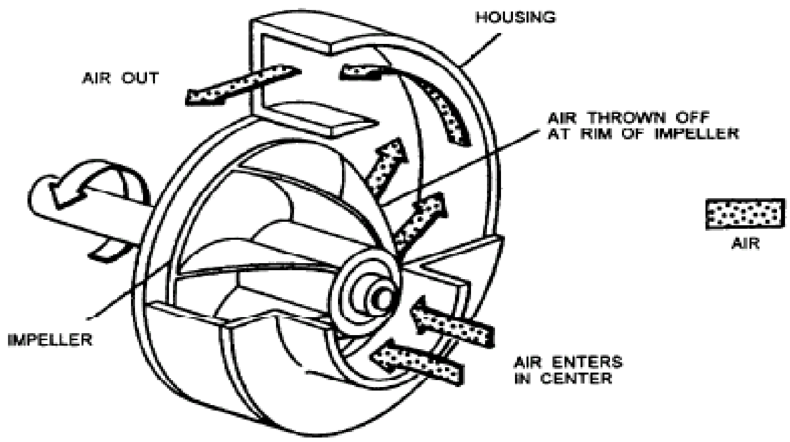

Figure 2.3 Cut view of centrifugal supercharger

2.1.3 Parasitic Losses

The largest problem of using a mechanical supercharger on a downsized engine is not the top-end performance, but the parasitic losses on part load. Miyagi et al., (1996) showed that for a Lysholm compressor only 20-30% of the parasitic losses come from mechanical losses and the rest from losses in the airflow, i.e. unnecessary pumping. Therefore, it is most important to try to minimize the airflow losses.

2.1.4 Clutch

The most obvious way of limiting the parasitic losses is to have a clutch to engage and disengage the compressor. Using a clutch has the advantage of reducing both losses in the air and the mechanical losses, assuming that the clutch is positioned on the crankshaft end of the belt. Since the compressor has a non-negligible inertia and that it rotates with high speed, it is necessary to apply large amounts of torque in order to accelerate the compressor to working speeds within reasonable time. These torque impulses will result in comfort problems if the work has to be taken from the crankshaft.

2.2 TURBOCHARGER

Turbochargers are commonly used in engines because they extract some of the energy from the exhaust gases that would have otherwise been lost [Corky Bell, 1997]. Turbochargers consist of a turbine (the component that is being spun by the passing exhaust gases) and the compressor (the component increasing the intake pressure) which is coupled to the turbine by a rotor. Figure 2.4 shows schematic layout of turbocharging system in a diesel engine.

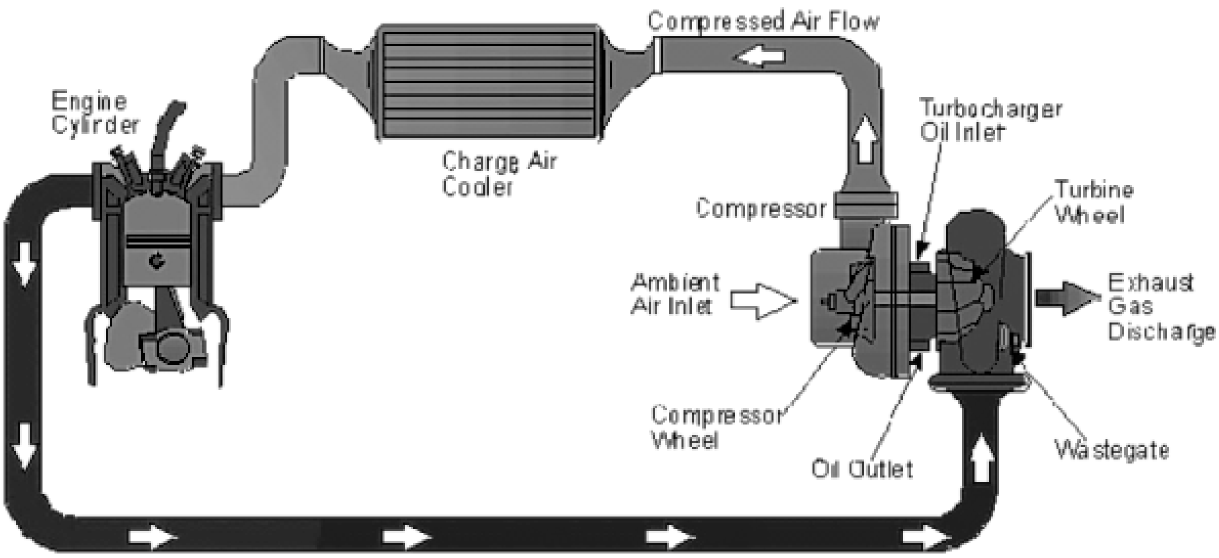

Figure 2.4 Typical schematic layout of turbocharger system of an IC engine

One of the advantages of turbochargers is that they are able to recuperate some of the energy of the exhaust gases. This makes turbochargers suitable for use in engines where efficiency is important, as well as for diesel engines that are otherwise not able to produce a high power. Another reason why turbochargers are preferred in diesel engines is because of the lower exhaust temperature [Cengel and Boles, 2006], which doesn't damage the turbine blades (unlike gas powered engines). Typically, turbines are very delicate and require special grades of oils because of their very high rotational speeds (sometimes exceeding 150000 rpm); as long with this in gas powered engine, the higher temperature of exhaust gases tends to melt the tips of the turbine blades which dramatically decreases the efficiency of the turbine which causes a significant decrease in engine power. In road going vehicles and race cars, turbochargers are well known for the turbo lag. The turbo lag is an unwanted effect and is caused because of the high turbine spool time due to the moment of inertia of the turbine and compressor. As well, it is due to the fact that the driving force of the turbine comes from the exhaust gases which are compressible. The turbo lag is in other words a delay in the turbine response

2.2.1 Waste Gate Operation

Some turbochargers are equipped with a waste gate [Figure 2.5]. This device allows some of the exhaust gases to bypass the turbine rotor at higher engine speeds**.** With this arrangement, the turbocharger can be designed to be more effective at lower engine speeds. The waste gate consists of a valve, actuator, and connecting linkage. The actuator consists of a diaphragm and spring enclosed in canister housing. The valve is located in an exhaust bypass line. Under low boost conditions, the spring pushes against the diaphragm moving the linkage to close the waste gate valve. Turbo boost pressure is directed against the other side of the diaphragm. As boost pressure increases with increased engine speed, the diaphragm moves against spring pressure to open the valve and allow a portion of the exhaust gases to bypass the turbine wheel through a connecting line. As boost pressure drops, spring pressure moves the diaphragm and linkage to close the valve. The waste gate is preset at the factory and no adjustment can be made.

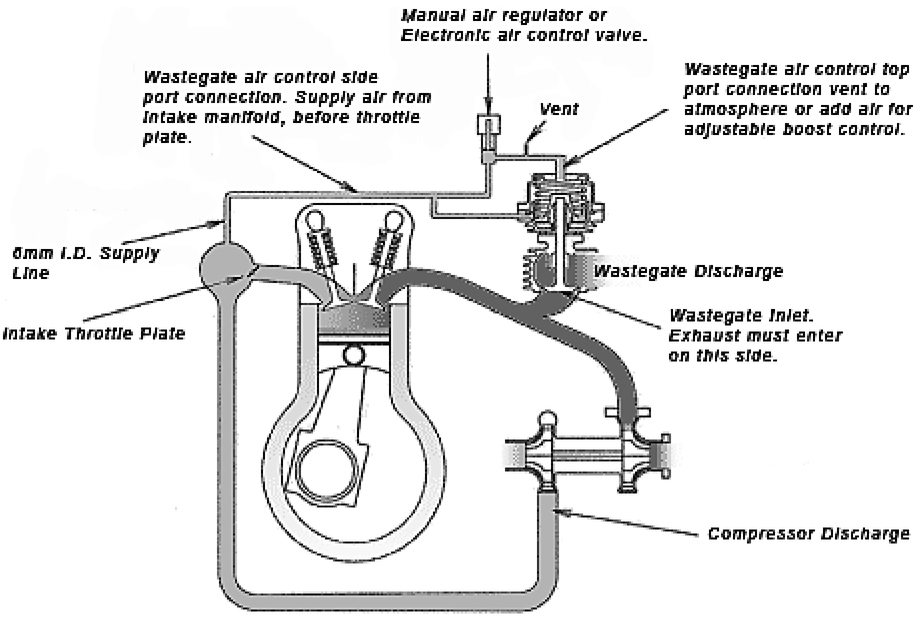

Figure 2.5 Waste gate arrangements in a turbocharged engine.

2.2.2 Trend of Turbo Charging Technologies

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. A fixed geometry turbine is not capable of supplying enough power to the compressor for the boost pressure required for low speed and during transient conditions. 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. In addition, the flow range of a centrifugal compressor is a limiting factor, and if higher boost pressures are demanded, it will be even more difficult to achieve satisfactory width of the usable range since the width of the compressor map becomes narrower as the boost pressure approaches its maximum.

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 turbo charging at low speeds, manufacturers are putting considerable effort into its development.

For a turbocharged engine with the Variable Nozzle Turbine (VNT), as is widely used in diesel engines, the boost pressure can be raised by controlling the variable nozzle at low engine speeds. Figure 2.6 shows an example of a VNT that was developed for use in diesel engines. In addition, improving the turbocharger efficiency in the region where the pressure ratio is high is important to reduce the turbine inlet pressure for high-pressure turbo charging.

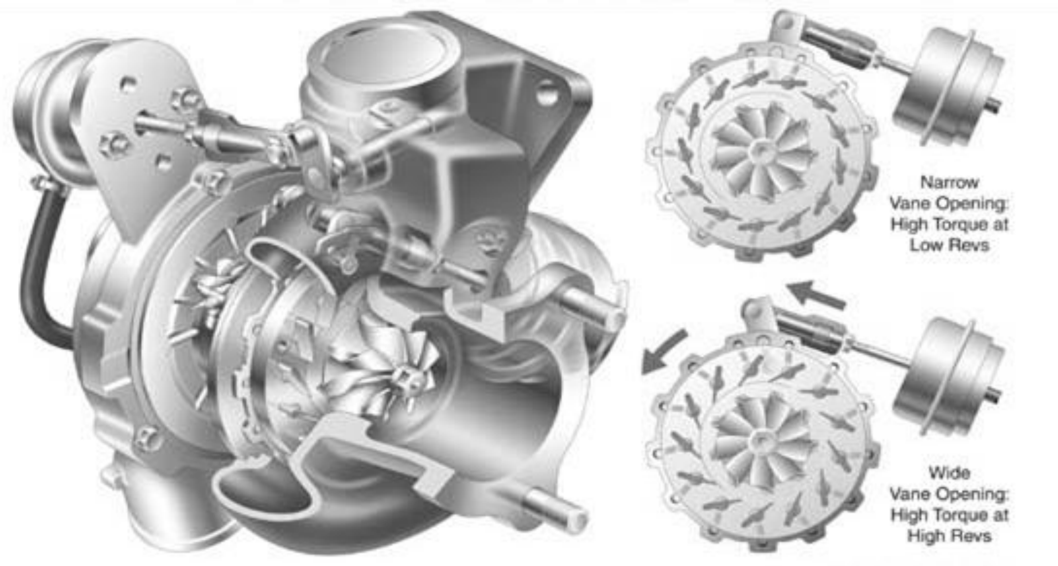

Figure 2.6 A typical example of a VNT that was developed for use in diesel engines

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. 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 Motor-Assist turbocharger (MAT), however, is able to raise the boost pressure at low engine speeds. So, by adding motor assistance, torque characteristics on a par with a large-displacement engine can be attained. A MAT can also recover thermal exhaust energy by acting as a dynamo at high engine speeds [Figure 2.7]. 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 is an important aspect of the development.

Moreover, the outer diameter of the permanent magnet cannot be made much bigger than already present 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 commercialized in large-scale turbochargers. 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.

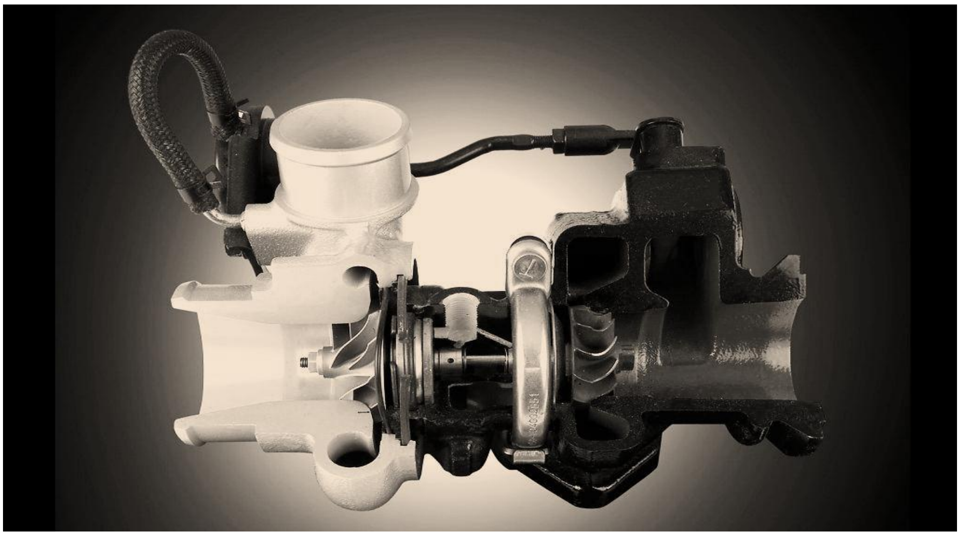

Figure 2.7 Schematic layout of a MAT.

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 eliminating the surge limit. The first is the application of two-stage turbo charging whereby the small compressor of the high-pressure turbocharger is used at low engine speeds. Unfortunately, a disadvantage of two-stage turbo charging is that the system is more complex and larger than single-stage turbo charging. 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.

The surge flow rate can be reduced by using a compressor with a variable inlet guide vanes (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.