New concept of two compression stages turbocharger

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Abstract: - The present paperwork proposes to present a new innovative and high efficient solution for a two compression stages that is the object of a brand new invention Patent. This paper presents a high efficient turbocharger that it is a viable solution in order to be adopted when the engine manufacturers looks for extra-power from any existing type of combustion engine. The solution is simple, elegant and compact and can be realized with the existing technology. Based on the analysis with the numerical simulation, the conclusion is that the existence of the second compression stage rotor improves greatly the output pressure of the device and shortens consistently the reaction time.

Key-Words: - Turbocharger, two compression stages, finite volume simulation, numerical simulation

1 Introduction

A turbocharger is a centrifugal compressor powered by a high speed turbine that is driven by an engine's exhaust gases. Its benefit lies with the compressor increasing the mass of air entering the engine (forced induction), thereby resulting in greater performance (for either, or both, power and efficiency). They are popularly used with internal combustion engines (e.g., four-stroke engines like Otto cycles and Diesel cycles). Turbochargers have also been found useful compounding external combustion engines such as automotive fuel cells.

The term turbocharger is a modern one, derived by shortening the turbosupercharger, which was widely used during the World War II era and earlier. This term refers to the fact that turbochargers are a specific type of supercharger, one that is driven by a turbine. The most common form of supercharger at the time, which was often referred to as a "geared supercharger", was mechanically driven by the engine, whereas the turbochargers are always driven by a turbine that gets its power from the engine's exhaust stream. Twinchargers combine a supercharger and turbocharger.

All naturally aspirated Otto and diesel cycle engines rely on the downward stroke of a piston to create a low-pressure area (less than atmospheric pressure) above the piston in order to draw air through the intake system. With the rare exception of tuned-induction systems, most engines cannot inhale their full displacement of atmospheric-density air. The measure of this loss or inefficiency in four-stroke engines is called volumetric efficiency. If the density of the intake air above the piston is equal to atmospheric, then the engine would have 100% volumetric efficiency. However, most engines fail to achieve this level of performance.

This loss of potential power is often compounded by the loss of density seen with elevated altitudes. Thus, a natural use of the turbocharger is with aircraft engines. As an aircraft climbs to higher altitudes, the pressure of the surrounding air quickly falls off. At 5,486 m (18,000 ft), the air is at half the pressure of sea level, which means that the engine will produce less than half-power at this altitude.

Fig.1. Cut-away view of an air foils bearing-supported turbocharger
The objective of a turbocharger, just as that of a supercharger, is to improve an engine's volumetric efficiency by increasing the intake density. The compressor draws in ambient air and compresses it before it enters into the intake manifold at increased pressure. This results in a greater mass of air entering the cylinders on each intake stroke. The power needed to spin the centrifugal compressor is derived from the high pressure and temperature of the engine's exhaust gases. The turbine converts the engine exhaust's potential pressure energy and kinetic velocity energy into rotational power, which is in turn used to drive the compressor.

A turbocharger may also be used to increase fuel efficiency without any attempt to increase power. It does this by recovering waste energy in the exhaust and feeding it back into the engine intake. By using this otherwise wasted energy to increase the mass of air, it becomes easier to ensure that all fuel is burned before being vented at the start of the exhaust stage. The increased temperature from the higher pressure gives a higher Carnot efficiency.

The control of turbochargers is very complex and has changed dramatically over the 100-plus years of its use. A great deal of this complexity stems directly from the control and performance requirements of various engines with which it is used. In general, the turbocharger will accelerate in speed when the turbine generates excess power and decelerate when the turbine generates deficient power. Aircraft, industrial diesels, fuel cells, and motor-sports are examples of the wide range of performance requirements.

In all turbocharger applications, boost pressure is limited to keep the entire engine system, including the turbo, inside its thermal and mechanical design operating range. Over-boosting an engine frequently causes damage to the engine in a variety of ways including pre-ignition, overheating, and overstressing the engine's internal hardware.

For example, to avoid engine knocking (pre-ignition or detonation) and the related physical damage to the engine, the intake manifold pressure must not get too high, thus the pressure at the intake manifold of the engine must be controlled by some means. Opening the waste-gate allows the energy for the turbine to bypass it and pass directly to the exhaust pipe. The turbocharger is forced to slow as the turbine is starved of its source of power, the exhaust gas. Slowing the turbine/compressor rotor begets less compressor pressure.

In modern installations, an actuator controlled manually (frequently seen in aircraft) or an actuator controlled by the car's Engine Control Unit, forces the wastegate to open or close as necessary. Again, the reduction in turbine speed results in the slowing of the compressor, and in less air pressure at the intake manifold.

In the automotive engines, boost refers to the intake manifold pressure that exceeds normal atmospheric pressure. This is representative of the extra air pressure that is achieved over what would be achieved without the forced induction. The level of boost may be shown on a pressure gauge, usually in bar, psi or possibly kPa. Anything above normal atmospheric level is considered to be boost.

In most aircraft engines the main benefit of turbochargers is to maintain manifold pressure as altitude increases. Since atmospheric pressure reduces as the aircraft climbs, power drops as a function of altitude in normally aspirated engines. Aircraft manifold pressure in western-built aircraft is expressed in inches of mercury, where 29.92 inches is the standard sea-level pressure.

In high-performance aircraft, turbochargers will provide takeoff manifold pressures in the 30- to 42-inchHg (1- to 1.4 bar) range. This varies according to aircraft and engine types. In contrast, the takeoff manifold pressure of a normally aspirated engine is about 27 in. Hg, even at sea level, due to losses in the induction system (air filter, ducting, throttle body, etc.).

All turbocharger applications can be roughly divided into 2 categories, those requiring rapid throttle response and those that do not. This is the rough division between automotive applications and all others (marine, aircraft, commercial automotive, industrial, locomotives). While important to varying degrees, turbo lag is most problematic when rapid changes in engine performance are required.

Turbo lag is the time required to change speed and function effectively in response to a throttle change. For example, this is noticed as a hesitation in throttle response when accelerating from idle as compared to a naturally aspirated engine. Throttle lag may be noticeable under any driving condition, yet becomes a significant issue under acceleration. This is symptomatic of the time needed for the exhaust system working in concert with the turbine to generate enough extra power to accelerate rapidly. A combination of inertia, friction, and compressor load are the primary contributors to turbo lag. By eliminating the turbine, the directly driven compressor in a supercharger does not suffer from this problem.

Lag can be reduced in a number of ways:
1. by lowering the rotational inertia of the turbocharger; for example by using lighter, lower radius parts to allow the spool-up to happen more
quickly. Ceramic turbines are of benefit in this regard and or billet compressor wheel.

2. by changing the aspect ratio of the turbine.
3. by increasing the upper-deck air pressure (compressor discharge) and improving the wastegate response; this improves performance but cost increases and reliability decreases.
4. by reducing bearing frictional losses; by using a foil bearing rather than a conventional oil bearing. This reduces friction and contributes to faster acceleration of the turbo's rotating assembly.
5. Variable-nozzle turbochargers greatly reduce lag.
6. by decreasing the volume of the upper-deck piping.
7. by using multiple turbos sequentially or in parallel.
8. by utilizing an Antilag system.

Lag is not to be confused with the boost threshold. The boost threshold of a turbo system describes the lower bound of the region within which the compressor will operate. Below a certain rate of flow at any given pressure multiplier, a given compressor will not produce significant boost. This has the effect of limiting boost at particular rpm regardless of exhaust gas pressure. Newer turbocharger and engine developments have caused boost thresholds to steadily decline.

Electrical boosting ("E-boosting") is a new technology under development; it uses a high-speed electrical motor to drive the turbocharger to speed before exhaust gases are available, e.g., from a stoplight. An alternative to e-boosting is to completely separate the turbine and compressor into a turbine-generator and electric-compressor as in the hybrid turbocharger. This allows the compressor speed to become independent to that of the turbine. A similar system that utilizes a hydraulic drive system and overspeed clutch arrangement was fitted in 1981 to accelerate the turbocharger of the MV Canadian Pioneer (Doxford 76J4CR engine).

Turbochargers start producing boost only above a certain exhaust mass flow rate. The boost threshold is determined by the engine displacement, engine rpm, throttle opening, and the size of the turbo. Without adequate exhaust gas flow to spin the turbine blades, the turbo cannot produce the necessary force needed to compress the air going into the engine. The point at full throttle in which the mass flow in the exhaust is strong enough to force air into the engine is known as the boost threshold rpm. Engineers have, in some cases, been able to reduce the boost threshold rpm to idle speed to allow for instant response. Bothlag and Threshold characteristics can be acquired through the use of a compressor map and a mathematical equation.

Some engines, such as V-type engines, utilize two identically sized but smaller turbos, each fed by a separate set of exhaust streams from the engine. The two smaller turbos produce the same (or more) aggregate amount of boost as a larger single turbo, but since they are smaller they reach their optimal RPM, and thus optimal boost delivery, more quickly. Such an arrangement of turbos is typically referred to as a parallel twin-turbo system. The first production automobile with parallel twin turbochargers was the Maserati Biturbo of the early 1980s. Later such installations include Porsche 911 TT, Nissan GT-R, Mitsubishi 3000GT VR-4, Nissan 300ZXTT, Audi RS6, and BMW E90.

Some car makers combat lag by using two small turbos. A typical arrangement for this is to have one turbo active across the entire rev range of the engine and one activates at higher RPM. Below this RPM, both exhaust and air inlet of the secondary turbo are closed. Being individually smaller they do not suffer from excessive lag and having the second turbo operating at a higher RPM range allows it to get to full rotational speed before it is required. Such combinations are referred to as a sequential twin-turbo. Porsche first used this technology in 1985 in the Porsche 959. Sequential twin-turbos are usually much more complicated than a single or parallel twin-turbo systems because they require what amounts to three sets of intake and waste gate pipes for the two turbochargers as well as valves to control the direction of the exhaust gases. Many new diesel engines use this technology not only to eliminate lag but also to reduce fuel consumption and reduce emissions.

![Fig.2. A pair of turbochargers mounted to an Inline 6 engine (2JZ-GTE from a MkIV Toyota Supra) in a dragster.](image-url)
The paper proposes a new concept of two compression stages turbocharger with compressor rotors placed in opposition installed inside a common housing, solution which is simplifying the construction and is making it in the same time more compact. The construction solution itself solves the problem of the reaction time (Lag) for the High Pressure compression stage when the engine demand for extra pressure is sudden.

Some of the main elements are to be seen in the figures below as follows: 3-Turbine rotor for the Low pressure stage (LP); 4-Turbine Housing; 5-Exhaust gases Low Pressure turbine duct; 9-Exhaust gases High Pressure (HP) turbine duct; 10-Turbine rotor for the High pressure stage; 14-Compressor housing; 15-High pressure compressor rotor; 18-Low pressure compressor rotor; 22-Inlet for exhaust gases for Low Pressure turbine; 23-Inlet for exhaust gases for high Pressure turbine.

How it works?
The exhaust burned gases coming from the engine are directed to the 22-Inlet for exhaust gases for Low Pressure turbine and 23-Inlet for exhaust gases for high Pressure turbine. They are putting in motion 3-Turbine rotor for the Low pressure stage (LP) and 10- Turbine rotor for the High pressure stage. 3 and 10 are placed on the same shafts with 15- High pressure compressor rotor; and 18-Low pressure compressor rotor which are delivering compressed air to the engine.

For normal functioning of the engine the HP compression stage is not working, and that is via a throttling valve for instance, the exhaust gases coming from the engine is feeding only 22-Inlet for exhaust gases for Low Pressure turbine and only 18-Low pressure compressor rotor is working whereas the 15- High pressure compressor rotor is still playing just a role of guiding and transforming the kinetic energy of the air in static pressure.

Once the engine demand for air is increasing the 23-Inlet for exhaust gases for high Pressure turbine receives exhaust gases and 10- Turbine rotor for the High pressure stage is delivering extra kinetic energy to the air and thus increasing the pressure of the air to feed the engine. Since the constructive
solution is very compact and between compression stages the distance/gap is extremely small, the reaction time is almost instantaneous and depends entirely only of the reaction time of the throttling valve.

3 Numerical simulation
Several numerical simulations (with finite volumes) were performed for various scenarios. The scenarios are covering the functioning of the device for 8000, 12000 and 16000 rpm and for delivered pressures from 0 bar (r) corresponding to atmosphere releasing to 0.5, 1, 1.5, 2, 2.5, and 3 bar pressure to the exit of the second stage of the compressor and which is supposed to be delivered inside the engine.

It will be presented only the simulation results for the rotors speed of 16000 rpm and 3 bar pressure to the exit of the second stage. The rationale for this simulation scenario is that 16000 rpm is somehow a mild value for a turbocharger to function whereas 3 bar output pressure is 50-70% higher than any existing commercial highly efficient turbochargers in which 2 bar is considered as being a value reached by the most competitive ones in the market. To these limit functioning values the behavior of the proposed turbocharger is numerically studied and analyzed.

The fluid domain geometry and the finite volumes elements grid are defined as in figure above. We used 214,168 finite volume cells with 52,192 nodes with 6 cell zones and 21 face zones in order to simulate the rotation of the rotors. In the figure are defined the inlet air area where the air is accessing the low pressure rotor (here the boundary condition is 0 bar (r) corresponding to atmosphere), the outlet air area from which the compressed air is leaving the turbocharger and where the boundary condition is 3 bar output pressure to feed the engine.

The air properties were defined as constant density 1.225 kg/m3 and constant viscosity of 1.7893 kg/m-s.

After several thousand iterations in which the stability of solutions was reached, the results are as follows:

3.1 Computed static pressure
In order to make explicit the results some sectioning planes were defined to capture the results for the inlet-outlet areas and the results profiles along the rotors as one can see in the below figure.

![Computed static pressure](image)

By analyzing the results one may see that the first stage compressor rotor is increasing the static pressure from 0 bar (r) existing to the inlet area to 7.18e04 Pa whereas the second stage is boosting the pressure from 7.18e04 Pa to 2.34e05 Pa. To the outlet area the static pressure is near 3 bars so that if the load of the proposed turbocharger is 3 bars then the device is working properly.

3.2 Computed dynamic pressure
As seen in the following figure, the dynamic pressure developed by the device is steadily increasing from 6.85 Pa at the inlet area to a peak of 2.06e05 Pa near to the outlet area. The second stage rotor is the most effective in increasing the values.

![Computed dynamic pressure](image)
3.3 Computed absolute pressure
As seen in the below figure, the computed absolute pressure developed by the device is steadily increasing from 7.62e04 Pa at the inlet area level to a peak of 3.99e05 Pa to the outlet area. The second stage rotor again is the most effective in increasing the values of the parameter.

![Computed absolute pressure](image1.png)

Fig.10.Computed absolute pressure

3.4 Computed total pressure
As seen in the figure below, the computed total pressure developed by the device is steadily increasing from 1.35e04 Pa at the inlet area to a peak of 3.07e05 Pa to the outlet area. The second stage rotor again is the most effective in increasing the values of the parameter.

![Computed total pressure](image2.png)

Fig.11.Computed total pressure

3.5 Computed total velocity fields
The total velocity of the fluid is defining the kinetic energy developed inside the device. As to be seen in the above figure the total velocity is increasing from 0 m/s in the inlet area to a maximum of 542 m/s right near the outlet area.

By comparing the velocity profiles computed in the first stage rotor and the second stage rotor, we may pull the conclusion that the second compression stage is the most effective in terms of imposed kinetic energy to the fluid.

![Computed total velocity](image3.png)

Fig.12.Computed total velocity

4 Conclusion
This paperwork is proving that the proposed high efficiency turbocharger is a viable solution to be adopted when the engine manufacturer is looking for extra-power from any existing type of combustion engine. The solution is obviously simple, elegant and compact, which can be realized with the existing technology.

By analyzing the numerical simulation, the conclusion is that the existence of the second compression stage rotor is greatly improving the output pressure of the device and is consistently shortening the reaction time.

This new turbocharger should be a must in the next generation of combustion engines.

References: