Mechanism Investigation:
Automotive Charging Systems

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Introduction

Since automobile engines require both fuel and oxygen for the combustion that drives the pistons, engines must draw outside air into the cylinders. The combustion reaction can create more explosive force if there are larger amounts of air and fuel in the cylinders, resulting in greater horsepower. While it is easy to control the amount of fuel involved in the reaction, getting large amounts of air into the cylinders is more difficult. According to Holset Engineering Company, there are two ways of doing this. The first is to increase engine size, but the resulting increase in weight rules out this alternative as uneconomical. Hence, engine manufacturers who wish to improve on naturally-aspirated engines, which simply draw in outside air at ambient pressure, must use charging systems.[1] These systems compress the ambient air that goes into the cylinders. Since the air is at a higher pressure, a greater mass of it can fit inside the cylinder, and this results in a more powerful combustion reaction.

Horst Bauer reports that there are three main types of charging systems: mechanically-driven superchargers, exhaust-gas turbochargers, and pressure-wave superchargers.[2] Holset dismisses the first class as outdated because the power source for the mechanically-driven supercharger is the engine itself. Thus, "theoretically a supercharger

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[1] n.a. *Turbocharger Fundamentals*. [Online] Available http://www.holset.co.uk/flash/index.html.
[2] Bauer, Horst, ed. *Automotive Handbook*. Stuttgart: Robert Bosch, 2000.

could increase a 200hp engine to a 275hp engine. However as it is an engine parasite it needs 50hp to operate [and] therefore only increases the engine to 225hp."[3] Obviously, this is still an improvement over naturally-aspirated engines, but there are greater efficiency gains to be made from the other two types of charging systems, which compress intake air with energy captured from engine exhaust. Thus, turbochargers and pressure-wave superchargers "recycle" the pressurized waste fumes of the combustion process.

While not required for cars to actually run, charging systems offer several attractive advantages for automobile designer and consumer alike. First, engineering consultant Richard F. Ansdale reports that charging systems can yield engine torque improvements of 20-35% over naturally-aspirated engines.[4] This gives vehicles more towing power and better acceleration. Holset suggests several other advantages to using charging systems, including better fuel efficiency due to "improved pressure balance across the engine," lower levels of emissions due to that greater efficiency, and "altitude compensation" because ambient air has even lower pressures at high altitudes and charging systems help compensate.[5]

While charging system failures would probably not be life threatening for automobilists, it is still fairly important that these mechanisms be reliable. First, high performance vehicles depend on all systems working properly, and sudden losses in power could disrupt the driver. Second, a catastrophic failure in which parts break loose or become detached could disrupt other systems in the vehicle. Finally, automotive

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[3] See 1.

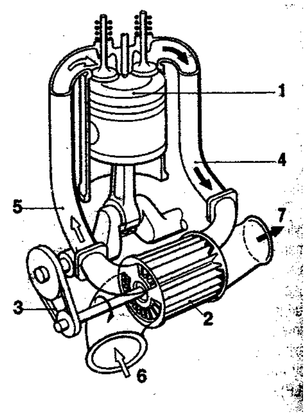
[4] Ansdale, Richard F. "A Reconnaissance of Supercharging Technology 1902-1980." *Turbocharged Diesel and Spark Ignition Engines*. Warrendale, PA: Society of Automotive Engineers, 1981.

[5] See 1.

repair costs can be high, and a reliable charging system means one less auto part to worry about fixing or replacing. Hence, we will attempt to evaluate these mechanisms.

Mechanism Descriptions

Charging Mechanism 1: Pressure-wave supercharger



Pressure-wave supercharger
1 Engine, 2 Cell rotor, 3 Belt drive,
4 High-pressure exhaust-gas,
5 Pressurized air, 6 Low-pressure air intake,
7 Low-pressure exhaust outlet.

Image from Bauer, Horst, ed. Automotive Handbook. *Stuttgart: Robert Bosch, 2000.*

The source of motion for the pressure-wave supercharger is the automobile's crankshaft. Of course, this is turned by the piston action of the car's engine; however, this assignment precludes discussion of this mechanism, and so we begin our analysis with the crankshaft. The shaft transfers its motion to a circular wheel to which it is rigidly attached. Hence, the wheel has the same angular velocity as the shaft. A point at the edge of the wheel, then, moves in a circular path with a linear velocity proportional to the radius of the wheel. Fitted around one half of the wheel is a belt, which ideally does not slip as the wheel rotates. Therefore, a single point on the belt moves with the same linear velocity as the point on the outside of the wheel. This motion enforces the familiar "no-slip" compatibility condition we have studied in class for rotational rigid body motion.

As one would expect, the length of the belt is much longer than the circumference of the wheel, and so the belt serves to transfer motion across a distance roughly parallel to the surface on which the car is traveling. This transfer is important because the rest of the supercharging mechanism must be located some distance away from the crankshaft so as not to interfere with its motion; after all, the primary purpose of the crankshaft is not to power the supercharger but to provide torque for the car's axle so it can actually travel down the road.

At the other "end" of the belt, that is to say the area at which the belt's direction circles back around toward the crankshaft, is another wheel, this one with a smaller radius. The belt contacts roughly one half of this wheel, and the belt length is chosen so that there is no slack in the belt. Summarizing this part of the mechanism, the larger wheel rotates, giving linear motion to the belt, and as the belt moves the second wheel simultaneously rotates. The combination of the "no-slip" compatibility condition at the second wheel and the fact that the second wheel has a smaller radius means that this wheel rotates with a higher angular velocity, since the velocity of all points on the belt is uniform.

The second wheel is rigidly attached to the end of another shaft, which, consequently, rotates with the same angular velocity. The other end of this shaft is rigidly attached to a fan-like assembly called a cell rotor, which rotates with the same angular velocity as the second wheel and shaft. The cell rotor consists of long, rectangular fins attached parallel to the axis of the shaft and extending radially outward, like the familiar paddle wheel on the back of a riverboat. A hollow cylindrical metal housing open at both ends encloses the cell rotor, which is necessary for the cell rotor to be able to do its job.

This job is to facilitate an exchange of energy, "using pressure waves to convey energy from the exhaust-gas to the intake air".[6] The mechanism for this process involves thermodynamics and fluid mechanics and is well beyond the scope of this course. However, it is easy to understand qualitatively, and Bauer's description of the process can be summarized by the following: Intake air moves past one end of the rotor cell before moving into the cylinders of the engine, and exhaust gas from the cylinders moves past the other end. As the cell rotor rotates in synchronization with the piston-firing rhythm,[7] pressure waves caused by the piston motion propagate through the air inside the rotor cell and transfer some of the energy from the exhaust gas to the intake air.[8] Hence, the intake air heats and expands. The increased pressure this causes forces more air into the cylinders, which is what the charging system needed to accomplish.

At this point, it is easy to see why the pressure-wave supercharger is such an improvement over traditional superchargers, which are entirely powered by the crankshaft. It takes significantly less power from the crankshaft to rotate the rotor cell than it would to power a compressor. Hence, while pressure-wave superchargers are, to use Holset's term, "parasites" (XXXX), they are significantly less parasitic than traditional superchargers because their primary source of energy is the kinetic energy of the hot exhaust gas, which otherwise goes unused, and not the kinetic energy of the pistons via the crankshaft.

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[6] See 2.

[7] I believe this synchronization condition must determine the radii ratio of the two belted wheels.

[8] See 2.

Charging Mechanism 2: Turbocharger

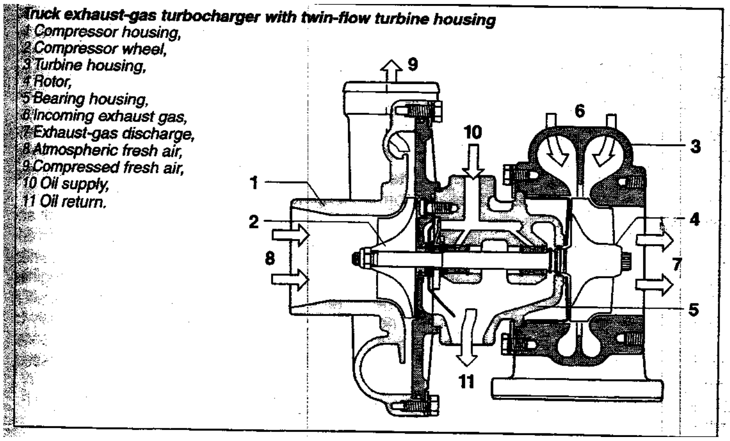

Image from Bauer, Horst, ed. Automotive Handbook. *Stuttgart: Robert Bosch, 2000.*

The turbocharger mechanism is definitely simpler than the pressure-wave supercharger. This is because, unlike in the first case, this mechanism gets its energy from one source rather than two. The result is a more linear device that leaves no doubt as to the source of motion—exhaust fumes. These fumes come out of the pistons hot and pressurized, and the turbocharger takes advantage of that. As Bauer points out, the device is essentially “a turbine and a compressor installed on a single shaft.”[9] Hence, pressurized fumes set in motion one rigidly connected apparatus that accomplishes the device’s task of compressing the intake air going to the engine. However, we can still examine each part of that apparatus.

The part of the turbocharger that the exhaust fumes actually contact is called the turbine wheel[10] or rotor[11]. A nozzle directs the fumes toward the rotor, and the pressure force from the fumes pushes against the fan-like blades of the rotor and causes it to spin. Since the rotor is rigidly attached to a shaft, the shaft rotates with the same angular velocity as the rotor. According to Garrett Engine Boosting Systems, this shaft is usually

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[9] See 2.

[10] MacInnes, Hugh. *Turbochargers*. Tucson: H.P. Books, 1976.

[11] See 2.

supported by a well-lubricated oil bearing. The oil level must be very carefully maintained, because the shaft should be able to rotate with as little friction as possible but must also be held very precisely in place. This allows designers to place the fume nozzle as close to the rotor blades as possible to maximize the gas' pushing force.[12]

This well-supported shaft is rigidly connected to a compressor wheel at the other end. Hence, the spinning of the shaft causes the compressor wheel to spin—again, at the same angular velocity. Whereas the fan blades of the turbine received their motion from gas, the blades of the compressor wheel give their motion to gas. As the compressor wheel spins, it sucks intake air toward it and forces it through a tiny gap, where it travels at a higher pressure to the engine cylinders. An analogous and easy to visualize device would be a large funnel attached to the outdoor side of a large window exhaust fan, with the nozzle pointing away from the fan. As the fan sucked hot air out of the room, it would compress the air by "squeezing" it all into the nozzle of the funnel. Having thus compressed the intake air on its way to the engine, the turbocharger has performed its function.

Comparison and Conclusions

While both charging systems are effective, I believe the pressure-wave supercharger is the better choice. The three most relevant criteria in making this judgment are performance, reliability, and cost. With regard to performance, Ansdale's analysis shows that pressure-wave superchargers can be 15% more effective than turbochargers.[13] Additionally, the pressure-wave supercharger does not suffer from turbolag. Integrated Publishing describes turbolag as "a short delay before the turbocharger develops

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[12] n.a. *Turbocharger Components*. [Online] Available http://www.egarrett.com/technology/tech_turbo_comp.jsp?justlist=1&l1id=1&l2id=2&l3id=7

[13] See 4.

sufficient boost" caused by the fact that "[i]t takes time for the exhaust gases to bring the turbocharger up to operating speed."[14] Because, as Bauer notes, "the actual energy-exchange process proceeds at the speed of sound" in pressure-wave superchargers[15], they don't suffer from this phenomenon. It seems, then, that the superchargers have turbochargers beat for performance.

I believe the two systems are roughly equal with regard to reliability and cost. Obviously, the turbocharger is a mechanically simpler device, with fewer points of motion transfer that could fail. However, the need to very precisely control lubrication in the bearing system for the turbocharger makes it at least as prone to failure as the pressure-wave supercharger. Similarly, while the supercharger has more moving parts, I believe they are simpler to manufacture than the parts for the turbocharger, which include carefully curved turbine and compressor blades that are no doubt more difficult to make than the supercharger's cell rotor.

Hence, with cost and reliability being roughly equal, the superior performance of the pressure-wave supercharger make it the preferable alternative to the turbocharger. However, both devices are significant improvements over conventional superchargers, which cannot provide the same performance as either of the devices we have examined because they fail to make use of available kinetic energy in the form of hot, pressurized exhaust fumes. Consequently, I have little doubt that as standards for fuel efficiency, emissions, and general performance continue to climb, these automotive charging systems will make their way into a greater number of vehicles.

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[14] n.a. *Turbo Lag*. [Online] Available http://www.tpub.com/content/construction/14264/css/14264_204.htm

[15] See 2.