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Professor Name: Pranab Kumar Mondal
Department Name: Mechanical engineering
Institute Name: Indian Institute of Technology, Guwahati
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Lec 38: Introduction to Turbocharger and Phenomenon of Turbo-lag in Turbochargers

I welcome you all to the session of engine system and performance and today we shall discuss about turbochargers. In the last class we have discussed about superchargers and we have seen that superchargers are used to increase the pressure of intake air and the increase in pressure will essentially increase the density of the incoming air and objective is to enhance the mass of air to be drawn into the engine cylinder during intake stroke. There are several avenues to increase the mass of air to be drawn into the engine cylinder but we have discussed increasing the engine speed is also associated with frictional losses then increasing the cylinder volume is not again a viable option. So, the only option which is there to increase the density of intake air so as to increase the mass of air to be drawn into the engine cylinder and if we increase the mass of air during intake stroke to be consumed by the cylinder, then certainly greater amount of fuel can be burned and power output from the engine can be increased or enhanced.

So, in this context, today we shall discuss about turbocharger. let us first discuss what is this and in which aspect this is different from supercharger. So, the concept of turbocharger was first proposed by Dr. Alfred J. Bucci in 1915, who developed this unit for a diesel engine.

Now, so this is the unit in a turbocharger. The entire unit or assembly is known as turbocharger. In this unit, a small turbine is there and that turbine is rotated by the exhaust gases of the engine and the turbine is connected via a common axle to a compressor and to increase the power output of the engine essentially by compressing the air above the inlet conditions so compressor is there to increase the density of the air above the inlet pressure and inlet conditions and to run the compressor there is a small turbine which is again rotated by employing or exploiting the kinetic energy of the exhaust gases now what we have learned.

In the context of a supercharger, superchargers are again nothing but compressors that compress the air to be drawn into the engine cylinder. Now, the compressor is rotated or driven by taking a certain amount of energy from the engine shaft. So, if we need to borrow some energy to run the compressor from the engine itself, or the engine's output power itself, then certainly we need to compromise with the engine's efficiency. Instead, what we can do here is use a turbocharger, which essentially has one small turbine that is rotated by the exhaust gases.

So, this particular turbocharger unit has a few advantages. What are those? Advantage number one is that it is small in size and used for larger flow rates. Number two is, if we talk about the turbocharger, it brings fuel economy. It has the capacity to reduce fuel consumption due to the fact that the energy, which would otherwise be lost into the ambience with the exhaust gases, can be used by the turbine or rather by rotating the turbine, can be recovered.

So, we have studied in our internal combustion engine course that exhaust gases carry some enthalpy. Now, that enthalpy will be lost if we do not use it properly. If we use that enthalpy to rotate a turbine, perhaps we can recover certain energy which otherwise would be lost. So that way, this has some advantage that brings fuel economy due to the fact that a certain amount of energy with the exhaust gas stream is recovered. So, these are the advantages.

But having discussed all these, advantages, there is still a disadvantage. What is that? That disadvantage is that using a turbocharger, it will be very difficult to produce higher pressure ratios. Rather, the sole objective is to increase the pressure ratio of the incoming or intake air, now using this turbocharger, it is not possible to increase the pressure ratio when the engine speed is low. That means if the engine speed is low, certainly the energy available with the exhaust gas is minimum, and hence the turbine cannot be rotated with high speed because, the turbine is rotated only due to the kinetic energy, or rather, it is rotated by exploiting the kinetic energy of the exhaust gases. So, this is a disadvantage. number one is being unable to produce high pressure at low engine speed.

I have already explained why it is so. That means we really cannot boost the pressure ratio, or we cannot bring, or we cannot have a higher-pressure ratio when the engine speed is low, the exhaust gas that is expelled from the engine has less energy as well. So, these are the disadvantages. Now, let us look into the hardware of this particular unit.

Let us first discuss what the components are within this unit, and then briefly its application. So, if we look at it, we can see that this is the entire turbocharger unit. In this, there are three components. So, the first component is number one: a compressor. Like what we have seen in the context of a supercharger, this compressor is dynamic. Typically, a centrifugal compressor is used and this compressor is mounted or incorporated with the intake manifold of the engine. Then, number two is a small turbine. That you can see. So, if you look at the upper part of this unit, it is the turbine.

So, this is the turbine. I will explain the operational process of this particular unit. A small turbine is attached to the exhaust manifold of the engine. So, you can see this. The lower part of this unit is the compressor, and that compressor you can see from the arrow. This is essentially ambient air which is drawn into this compressor. That air is compressed by rotating the runner of the compressor, or rotor of the compressor—to be precise, the rotor of the compressor is used to rotate and compress the air. In this direction, compressed air is coming out, which is again fed into the intake manifold, and it is eventually drawn into the engine cylinder.

Now, this compressor is connected to this turbine, so we have a common spindle. So, that is the common shaft, to be precise. So, in this common shaft, both compressor and turbine, these two units are mounted and the upper part of this unit is the turbine, as you can see. So, this is the turbine for the engine exhaust gases. So, exhaust gases that are expelled from the engine cylinder are allowed to go into this turbine. Those gases have high enthalpy and kinetic energy, which is used to rotate the turbine wheel and eventually do some work. Those gases eventually come out and lead through this pathway. So, as the turbine is rotating because of this movement of the exhaust gases.

Since these two units are mounted on this common spindle, the compressor will be rotating. By virtue of this rotation, the air which is drawn in from the ambience can be pressurized and that is the objective. So, there is a common spindle. It is used to mount both the compressor and turbine, and the spindle is supported by a pair of fully floating bearings.

So, plain bearings are there. the common spindle is supported by a pair of fully floated plain bearings. Essentially, you can understand bearings that we have studied in our machine design course. Bearings are machine elements, and these elements bear some load, static as well as dynamic. So, the common spindle is supported by a pair of fully floated plain bearings and this common spindle houses both the compressor and turbine. By rotating the turbine, we can rotate the compressor.

So, this is all about the hardware of this turbocharger. Now, let us talk about the mechanism. If we talk about this compressor or dynamic compressor, this compressor has two parts. One is the rotor, which is the rotating element another one is the diffuser.

So, these two parts are important to increase the pressure of the air as it moves along them. So, the dynamic compressor has two components or two parts. One is the rotating element, which is the rotor, and another one is the diffuser. So, these two components are responsible for raising the pressure as the air moves along them. So, this is the compressor and we have studied turbines. Perhaps you studied steam turbines or gas turbines. So, this is also a gas turbine, but the size is very small. So, this particular unit, the turbocharger, is used. In marine diesel engines, rather, the application of turbochargers spans from marine diesel engines.

So, applications of turbochargers. So, the applications span from marine diesel engines to vehicle diesel engines. Sometimes, they are also used in boosted SI engines. So, sometimes, if we need to increase the pressure ratio of the SI engine, that is, in boosted SI engines, turbochargers are used.

So, these are the application. I forgot to mention one important element. See compressed air that comes out from this compressor is not directly taken to the engine or rather intake manifold. Sometimes depending on the requirement and in particular, if this unit is used for the SI engines, we need to have one aftercooler or intercooler.

The sole purpose of this particular unit is to take off certain amount of heat from the compressed air. As the air is getting compressed inside the compressor, its pressure will increase, but with the increase in pressure, thermodynamic consideration will be there, that is temperature also will increase. So, the rise in temperature, if it is beyond certain limit, essentially, in the intake manifold, again the consume air should be compressed during compression stroke. So, an increase in temperature associated with increase in pressure inside the compressor will be further enhanced inside this engine cylinder and that increase in temperature will eventually invite one important or other detrimental problem is which is knock. That is knock is really a severe detrimental problem for the SI engines, so for the SI engines, if we use turbocharger before this compressed air enters into the intake manifold one intercooler or aftercooler will be there essentially to take up certain amount of heat from the compressed air itself or compressed air stream. This intercooler may not be required for the CI engines because knock is not a serious problem for the CI engines, so these are the applications.

And, for a typical IC engine flow rate and pressure ratio because flow rate here refers to the flow rate of the charge essentially that is the flow rate of exhaust gases and pressure ratio, the speed of turbocharger Try to understand here speed of turbocharger refers to speed of the turbine which in turn is equal to speed of the compressor as well. Because these two things or these two rotating elements or rotating machinery are mounted on a common spindle or common shaft.

So, the speed of a turbocharger of the order of even 10^6 rpm is not uncommon; rather, it is common. So, this is what is very important. Now, let us talk about, one important thing: we have discussed turbochargers, then we have talked about, the description of a turbocharger. So, let us talk about one detrimental aspect or detrimental effect associated with the operation of a turbocharger. So, problematic issue with the operation of a turbocharger, this is known as turbo lag. So, what is turbo lag? So, these are the questions. So, the phenomenon of turbo lag in turbochargers we need to know. We have discussed the compressor, small turbine though any mechanical component we have discussed in this course, as well as the electronic control unit. In earlier engines, control of exhaust and inlet valves typically was monitored, or controlling of the operation of inlet and exhaust valves was monitored using a cam and follower mechanism. So again, cam-follower mechanism or cam and follower—all these are mechanical components. Any mechanical component we discuss or we consider has certain inertia. So, no matter how light or how precise you make it, there is some inertia associated with the rotating mass.

Similarly, in the context of this unit, which is the turbocharger, so, if the engine is accelerated, certainly, understand the engine speed will increase. If that is the case, then the exhaust gas flow will increase. We have discussed today that the turbine is rotated solely by the kinetic energy of the gas or gases that are expelled from the engine cylinder. Now, with the sudden acceleration of the engine, the engine speed will increase, the exhaust gas velocity will increase, but there is a delay in delivering the energy that should be discharged into the turbine housing to speed up the wheel. So momentarily, maybe the exhaust gas speed will increase, but momentarily the turbine wheel won't be able to speed up. So, there is a delay.

And that delay is essentially associated with the inertia of the rotating mass or the inertia of the wheel. So, this delay is known as the transitional period. So, there is a transition between the increase in the kinetic energy of the exhaust gases and the corresponding increase in the speed of the turbine wheel. This delay is known as turbo lag. A few lines about what turbo lag is, if this is the question, then let me write the answer: when the throttle valve is opened quickly, that means we need to accelerate the engine. If it is opened quickly, the turbocharger essentially needs to essentially to accelerate the engine speed or engine or rather automobile. The turbocharger will not respond as quickly as supercharger does. So, if we need to accelerate the engine, suddenly kinetic energy of the exhaust gases will increase but the increase in kinetic energy should be discharged into the turbine wheel and then turbine wheel will be able to rotate in line with the increase in kinetic energy of the exhaust gas. Even though there will be certain delay to deliver the excess energy to the turbine housing to speed up the wheel and this delay or transitional delay is known as turbo lag in the context of turbocharger operation. So, number two is during this transition period a very little improvement in the cylinder filling process will be there, this line has some significance, so that means as the turbine is as the engine speed is or if the driver is accelerating, the engine we need to supply high pressure or greater mass of air to be drawn into the greater mass of air to the engine cylinder only then we can burn larger amount of fuel and the sudden acceleration would be justified. But if we need to supply greater mass of air then the compressor will run in line with the requirement of the engine.

If we need to run compressor which is connected to the turbine, turbine will be able to run at a high speed but the turbine is not responding as quickly as supercharger that is if the compressor is connected to the shaft of the engine itself in that case compressor will be able to supply required amount of air needed or as needed by the engine. So, this is very important and if we go to the next slide this transitional response is known as Turbo lag of the Turbocharger. Certainly, from the discussion, you can understand this undesirable phenomenon. So, this is not desirable at all. This undesirable phenomenon associated with the rotating inertia or polar moment of Inertia of the rotating mass or part of the turbine.

So that you have studied in your machine design or dynamics of machinery course, what is polar moment of inertia, rotating inertia, can be written as

$$I = mK^2$$

Where m is the mass of the rotating element, rotating element, and K is the radius of gyration. So. The turbine wheel is having certain mass, that is the mass of the rotating element or rotating part. What is the radius of gyration?

So, that is the distance from the axis of rotation to a point where all the mass of the rotating element or rotating body is assumed to be concentrated. So, that you have studied in your dynamics of machinery course. So, radius of gyration, that is the distance from the axis of rotation to a point where all the mass of the rotating element is assumed to be concentrated. Now, the question is, knowing the polar moment of inertia I, so torque required to rotate the wheel, or rotating element in a generalized form, that T should be equal to

$$T = I\alpha \qquad (1)$$

Where T is torque and this α is the angular acceleration, I is polar moment or rotating inertia.

So, if it is the case, then from equation number 1, we can see that this angular acceleration is what we need. In line with the certain acceleration of the engine speed or engine or automobile, we need to rotate the wheel. So, the angular acceleration is inversely proportional to the polar moment of inertia. So, just having the polar moment of inertia, we can double the angular acceleration. So, one way of alleviating or circumventing the problem associated with turbo lag could be to use a light ceramic material for the wheel of the turbine, perhaps the polar moment of inertia, rotating inertia, can be reduced, which in turn will ensure a little improvisation of the turbine wheel in the context of turbo lag. But the question is, whenever someone considers lightweight ceramic material for the construction or fabrication of the turbine runner.

About the material such that it will be able to withstand high pressure and high temperature because exhaust gases carry enthalpy, have some pressure, and high pressure and high temperature. So, the material must be able to withstand those particular thermodynamic conditions without any mechanical failure. So, this is what is important in this context. Here, one important point to significantly reduce the turbo lag purely from the perspective of better operation of the turbocharger. There could be two avenues: the first one is to reduce the polar moment of inertia, that is, to use lightweight material, or the other avenue could be to use a variable geometry turbine, and this is called VGT. So, either we can use lightweight ceramic material to reduce the polar moment of inertia, or else we can use a variable geometry turbine or VGT purely from the perspective of better operation of the turbocharger.

So, for this particular case, someone should consider the thermodynamic aspects like high pressure and high temperature conditions of the material. But if we look at the second one, that is also a really viable option. So, if we use a variable geometry turbine.

We shall discuss this part later in this class. But let us talk about the turbines used in turbochargers, are categorized into two subclasses—one is fixed geometry turbines. which are known as FGT, and number two is variable geometry turbines, and this is VGT. So, if we, consider this particular case first, we should know why fixed-type or fixed geometry turbines are not suitable for turbochargers.

Then only we can discuss this one. So, if we talk about FGT, that is fixed geometry turbines. So, from the name itself, you can understand in this particular case the geometry of the compressor and turbine is fixed. So, the compressor geometry and turbine geometry—these two geometries are fixed for this case. So, geometry of the compressor, plus geometry of the turbine fixed and if the geometries are fixed, then for this particular case, the boost pressure—that is, rise in pressure—is solely determined by the rate of exhaust gas flow. So, if we need to boost the pressure, for a wide speed range of the engine, because the engine can be throttled fully or partially depending on the requirement. So, if we need to have a turbocharger with fixed geometry turbine solely by the exhaust flow, then to boost the pressure ratio for a wide range of speed, the turbochargers need to be operated at a large speed, large pressure ratio for the range of flow rates. And not only that, if we use turbocharger which is equipped with fixed geometry turbine, and we have seen that in fixed geometry turbine, boost pressure is solely determined by the exhaust flow. So that means if we need to boost pressure of the engine, so, if we need to boost off or if we need to boost the pressure of the incoming air for a wide range of engine speed, turbochargers need to be operated at high speed and high-pressure ratios for the range of exhaust flow rates.

Not only that, when the turbochargers are operated with or at high speed and high-pressure ratios, typically, turbochargers are required to be protected from two, again, detrimental effects, and these two effects are known as overspeeding and overheating. So, fixed geometry turbine, if we use to boost high pressure turbine, over load of wide speed range, then enter turbochargers need to be operated at high speed.

Certainly, rotational then high at high pressure ratios over a wide flow range of the exhaust gases and if that is the case, this aspect, demands that turbochargers, has to be protected from two detrimental effects. And if we go to the next slide two detrimental effects are number one over speeding and number two overheating. What these two detrimental effects are? Now, the question is what is over speeding, you can understand when turbine and compressor these two components are rotating at high speed so essentially to boost the pressure, that high rotational speed, rather components of these two elements when they are rotating at high speed, and when these components are in touch with high pressure, high temperature exhaust gas, in particular turbine, because this is the fixed geometry turbine, so when turbine runner is rotating at high speed to boost the pressure, and when the turbine blades are in touch with high-pressure, high-temperature exhaust gas or exhaust gases, that particular condition may destroy the revolving components of the turbocharger or turbine. So, this is detrimental. And this is known as overspeeding.

The prevailing situation can destroy revolving components. So, this is the overspeeding effect. So, this is not only the turbine; the compressor can also encounter such problems, heating issues. So, if we go to discuss overheating, then overheating—what is overheating? We have discussed that when the pressure of the intake air is high, and that is what we need because we need to increase the pressure of the intake air, which in turn will increase the density and certainly the mass of the intake air can be increased. When the pressure of the intake air is high, this high-pressure air will be drawn into the engine cylinder, and in subsequent stages. So, the consumed air will be compressed further during the compression stroke of the engine. So, what will happen?

The pressure of the air will increase further the engine cylinder to be precise during the compression stroke. So, this rise in pressure will be again associated with a rise in temperature. So that situation—so the rise in pressure will be increase the temperature as well. And this rise in temperature over a duration of time may become detrimental and destroy several components of the engine.

When the pressure of the intake air is high, that high-pressure intake air will be drawn into the engine cylinder. In the subsequent stroke, that is, the compression stroke, its pressure will increase further, which will be accompanied by a rise in temperature as well. And the temperature may become high enough to cause the complete failure of several parts of the engine and this phenomenon is known as overheating.

So, this will destroy several parts. Parts of the engine, several parts or components of the engine, so this is known as overheating. So, what you can understand is that if we use, a fixed-geometry turbine where the geometry of the compressor and the geometry of the turbine are fixed and the pressure or boost pressure is solely determined by the exhaust gas, we have encountered these two different aspects: overheating and overspeeding. Over and above, there is another problem. So basically, if the geometry accounting for all these problematic issues—if we need to reduce the speed of the turbine or even the compressor. So, if we need to reduce the speed of the turbine, the compressor speed will also decrease.

And if the compressor speed decreases, we had discussed in the previous class that in a performance map, compressor operation is restricted between two lines. One is the choke line, another is the surge line. The surge line means that is the zone where the compressor is operating at a low speed. So, if the compressor needs to be operated at low speed, accounting for all these problematic issues of the turbine itself, then at low speed, the compressor flow may be highly unstable. It will encounter surge, that is, flow reversal will be there. So, considering all these things, fixed geometry turbines are not even suitable. They are used in turbochargers, and hence, variable geometry turbines are used.

So, we shall discuss this turbine—that is, the variable geometry turbine. The need for this in the context of turbochargers has been discussed in today's class. What is a variable geometry turbine, and how does this particular turbine, safeguard turbochargers, that we will discuss in the next class.

With this, I stop here today.

Thank you very much.