Aerodynamic Design of Axial Flow Compressor & Fans
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Lecture 34
Design Strategies (Contd.)

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Hello, and welcome to lecture 34. We started talking about design strategies. Initially, in last lecture we started discussing about the preliminary design concept, then we were discussing about the design point selection.

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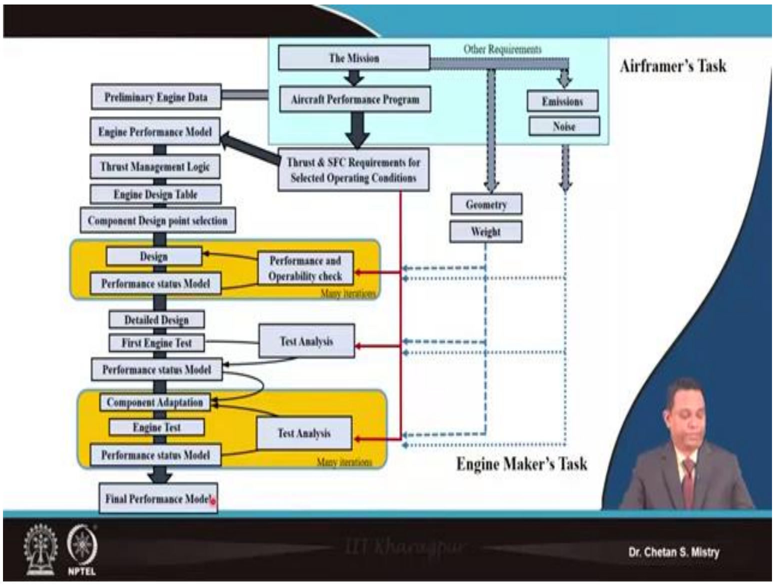

Let us summarize what all we were discussing in last session. So, we can say, for a particular engine design that's what is application to say aero engine or say for aircraft, the whole work that's what has been distributed in two forms; first, that's what is say airframer's task and second, that's what is engine designer's task.

And if you look at, so mission, that's what is our requirement of thrust, say our operating conditions, speed, all those parameters, they are been given by airframer's and based on that they are expecting special kind of performance. Suppose, if we are talking about say engine application to commercial aircraft there our requirement, that's what is mainly on in terms of say your thrust and specific fuel consumption and we are trying to have say fuel efficient engine.

When we are talking about the military application, they are having special operations to be performed and that's what is required special kind of attention. So, based on what is our thrust requirement and specific fuel consumption that's what is expected, the engine performance model that will be generated by the engine designer group.

Then they will be doing say how they will be addressing the thrust management, specially for say military application. Initially, the initial design parameters that will be calculated based on gas turbine cycle analysis and as per the requirements some of the constraints there have been kept for say initial design consideration.

So, when cycle analysis that's what is been done, that time some of the constraint initially only we are putting. So that, in later part that will reduce the number of iterations required. So, here if you look at, we are having say design model, we are having performance model and based on that we will be checking with the operability and this is what is required number of iterations.

Again, here the geometry and weight that will be coming into the picture and that's what is required attention from the airframer. So, they need to have clearance from what all calculation they have done whether it is meeting with the requirement or not, if not then again they need to go with the iteration from initial cycle analysis.

Then later part, once, these dimensions and this weight consideration all those things that's what is meeting with the requirement, next step will be going into detail design. Once we are going for detailed design, it may be required some new kind of technologies. So, these technologies need to be verified experimentally as well as computationally.

So, in order to have experimental verification, they need to go with say rig testing, it may be for compressor, it may be for turbine, it may be for combustion chamber, even for nozzle, even for intakes also, people, they are doing that kind of testing because that's what is a special attention that's what will be required by airframer as well as by the designers.

Once this is what is been done then those components that will be adopted for say further verification and for further adoption for the use then the engine testing that will be done. So, based on performance test analysis it may be going for say number of iterations, again here, the geometry and weight that will be coming into the picture, so the concern from airframer that will be coming into the picture.

Once all this requirement, expectations from the engine both from engine designer as well as from airframer that's what is getting verified and say that's what is say fulfilling all requirement then final performance testing that will be happening. So, you can say, this whole design program that's what is of long duration work.

Earlier days, people, they were taking almost more than 10 years for making of new engine with upgradation of technology with the availability of computational tool, maturity and available past data. These days, this cycle that's what has been reduced to maybe five to six years. So, that's what is the advancement in the technology for say development of gas turbine engines especially application to aeroplanes.

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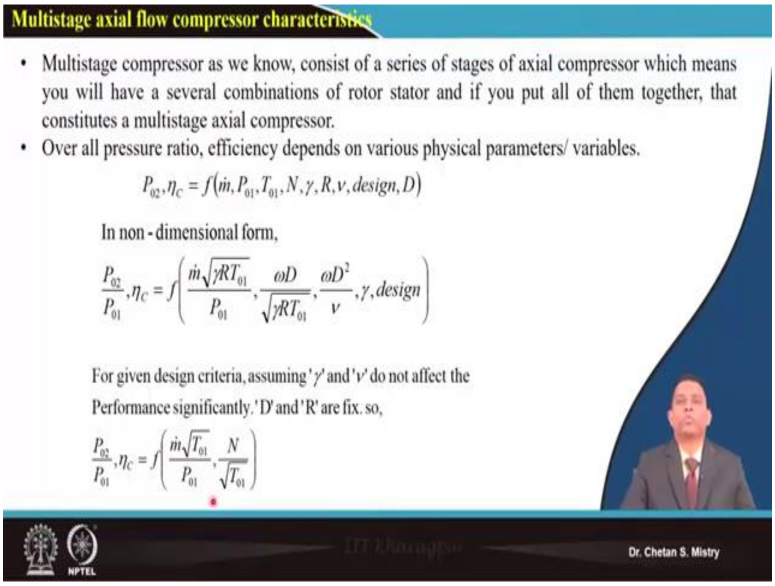

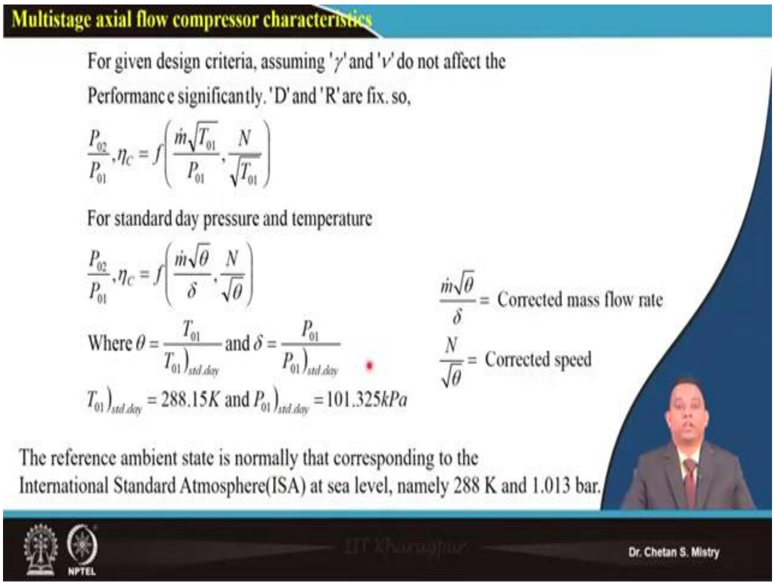

Now, before going into the detail, for say our design strategy, let us understand what we mean by performance parameters. So, if we say, we are having multi-stage axial flow compressor it may be say LP compressor, it may be say HP compressor, so for both kind of compressors it is made up of number of stages and we are interested in overall performance. When we say overall performance, our major concern is say overall pressure ratio and second parameter, that’s what we say as an overall efficiency or we can say per stage efficiency.

So, if we are looking for this kind of pressure ratio and we can say efficiency, that’s what is a function of say mass flow rate, what is my inlet pressure, inlet temperature, what will be my speed, specific heat ratio, gas constant, radius ratio, design strategy and we can say geometrical or characteristic dimension.

So, by using our Buckingham π theorem, if we will simplify and we will be forming that into non-dimensional form, it says my pressure ratio and efficiency that’s what is a function of say this is what is my mass flow rate parameter, it is $\frac{\dot{m}\sqrt{\gamma R T_{01}}}{P_{01}}$; this is what is my speed parameter that’s what is $\frac{\omega D}{\sqrt{\gamma R T_{01}}}$; $\frac{\omega D^2}{\nu}$, say this is what is my specific heat and this is what is my design parameter.

Now, when we are talking about say particular design criteria, we are assuming our γ and this ratio that’s what is not being affecting. And at the same time D and R also we are taking as a fix. So, basically, we are trying to reduce the number of parameters that’s what will be affecting on our two parameters that’s what is pressure ratio and efficiency. So, that’s what will be coming in sense of mass flow parameter and speed parameter.

If you look at, it says my mass flow parameter that's what is depending on mass flow rate, my entry temperature, my say entry pressure, same way my rotational speed and my entry temperature. So, if you look at, all the performance maps which are available for particular kind of compressors or say for engines they are defining the performance map in this form.

Again, here this temperature and pressure that's what is people they have modified based on say standard condition. So, here if you look at, this is what has been modified based on say $\frac{T_{01}}{T_{01})\_std.day}$ and this is what is my $\frac{P_{01}}{P_{01})\_std.day}$. So, you can understand here, this is what is been replaced by θ and δ. So, this standard condition it is nothing but it is 288.15 K for temperature and 101.325 kPa, that's what is for my pressure.

So, now if you look at, my pressure ratio and efficiency in all charts we are getting in the form of say corrected mass flow rate and corrected speed. So, now onwards we will not be saying say mass flow rate parameter and say your speed parameter, we will say, corrected mass flow rate and corrected speed. This, what we say as a standard condition, that's what is based on international standard of atmosphere, okay, and that's what they are calculating based on sea level condition.

So, all engines or all compressors, all components which are been designed they are been tested at particular condition. So, you can realize, whether or your aircraft that's what is flying in India or it is flying say in a western country or in a eastern country, the effect of my inlet pressure and inlet temperature that's what has been rectified by using this chart, that's what is the use of this parameter. We will be using this parameter when we are doing our design and that is the reason why these parameters they are been introduced here.

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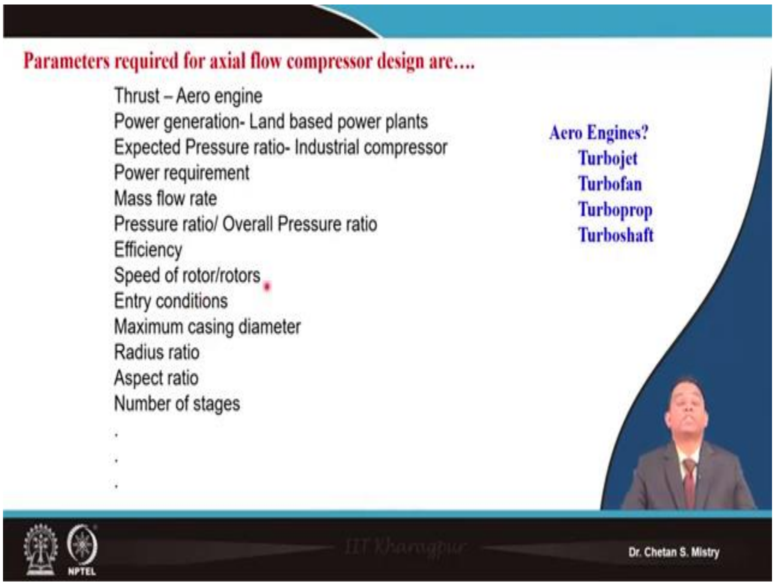

Now, let us see, suppose say, we want to have design of say axial flow compressor then the question will come what all are the parameters which are been required. So, very first question that will be coming is what is my application, where I want to use my axial flow compressor. So, suppose if I consider, I am looking for aero engine then very first parameter that will be coming into the picture that's what is say thrust. If I am looking for say power generation purpose, that's what is say for land-based power plant then that power that will come as one of my important parameters or required parameter.

Suppose if I consider, I am having say industrial application then we are looking for what will be my expected pressure rise. So, which kind of fluid we will be using and what pressure ratio we are expecting that's what is of our requirement, okay. Now, once this is what has been decided with you can understand for say your industrial application the power requirement that's what will be of major concern. It may be possible because of my high-pressure requirement, we may need to go with say small power plants in order to run this say compressor.

So, this power requirement that is also one of the concern parameter when we are looking for say special applications. Next parameter, that's what will be coming into the picture, that's what is mass flow rate if I am talking about my thrust; we can understand, thrust we are defining as say mass flow rate into say exit velocity. So, what is my mass flow rate going through my engine that's what is very important, okay.

The next parameter, that's what we will say, it is an overall pressure ratio or say per stage pressure ratio; we are looking for overall pressure ratio what we are expecting. So, if we are looking for say our commercial aircraft application where our thrust requirement is very large under that condition my overall pressure ratio will be larger.

Suppose, if I am consider say my land-based power plant where my expected power generation will be large for that also my overall pressure ratio will be very large. Next, we are concerned with our fuel economy for all the application, that is the reason why efficiency that definitely will be coming into the picture.

Next, we are looking for what will be my speed of the rotor or the speed of rotors because that's what is basically deciding what will be my dimensions of the engine. When we are talking about application for aero engines there this is of major concern. Same way if you are looking for say our industrial power plant, there also, because of say our cost constraint, it may be possible that we are looking for more in sense of say having speed to be in the limit of stress. So, stress limit for both turbine as well as for say compressor, that is the reason why this speed that is also important parameter.

Next, that's what we say is entry conditions. So, where I will be using my compressor that's what is important. Suppose, if you are considered say we are designing our HP compressor then my entry condition will be high pressure and high temperature, when we are designing our say low pressure compressor or say for fan, there we will be having our entry condition to be lower pressure and lower temperature.

So, entry condition that is also equally important. Suppose if we are considering say application for industries, there also at what pressure and temperature my fluid is coming that is of major concern.

Now, next we say, what will be my maximum casing diameter. If you will be fitting this axial flow compressor for aero engines; yes, this is what will be my constraints. Suppose, if I am talking about application for power generation in land-based power plant where casing diameter may not be the constraint for us. But this is what need to be known to us.

We can say what will be my radius ratio, then we can say what need to be my aspect ratio, how many number of stages, yes, this is what is very important. So, if you recall in last week we were discussing about all these parameters which are of importance for when we say design of axial flow compressor. There are many parameters of such kinds, okay.

Now, all of this if you look at, say…it says when we are talking about aero engines then the question will come, which kind of engine we are designing or say we are designing our axial flow compressor application to where, is it for turbo jet engine? Is it for turbo fan engine? Even in turbo fan, it says is it high bypass ratio engine or low bypass ratio engine, is it applicable for say turboprop engine, is it applicable for say turboshaft engine? So, all these things that's what need to be known to us when we are starting our design.

Remember one thing, what all we are talking it may be possible when you start doing your design you may be designing maybe fifth stage of HP or maybe first stage of say LP. So, for all this, these all parameters they are of great importance and we need to systematically go for these parameters to be selected, okay.

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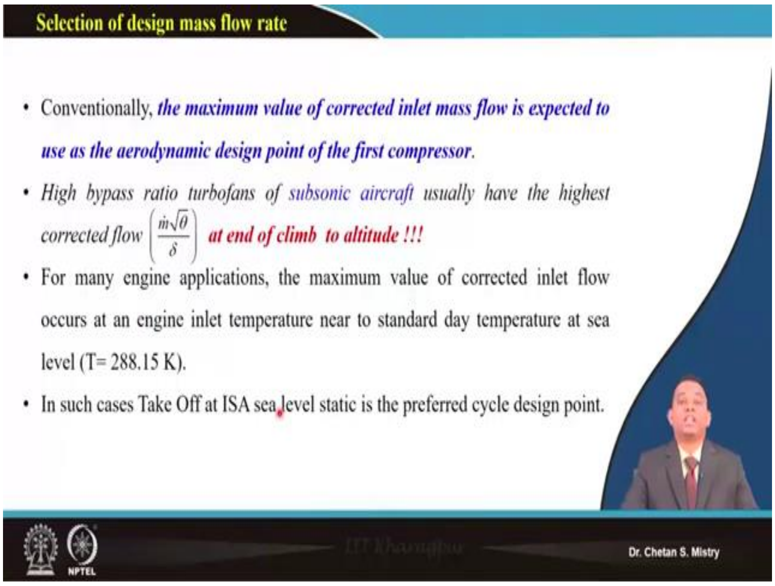

Now, very first parameter as we have discussed, that's what will be the mass flow rate because that's what will be deciding what will be my performance of whole engine and how my performance will be happening with my axial flow compressor. So, what it says, conventionally maximum mass flow rate condition that's what is expected to be used for design of say your first stage of compressor.

So, you can say, what is my maximum mass flow rate condition, it says if you are talking about aero engine, my maximum thrust requirement that's what is at the take-off condition, okay. So, you can say, that's what we can be considered as say maximum mass flow rate condition. But it was been found for high bypass ratio engines when we are talking they are flying at the subsonic speed, the highest mass flow rate that's what is happening at the end of climb at particular altitude.

So, you can say, what we are assuming as a maximum mass flow rate condition at say our ground level when we are saying we are having take-off condition it may need to give some misconception or maybe few percentage less mass flow rate. But it is universally been accepted as we have discussed, people they are doing say corrected mass flow rate condition for the design and that's what is based on ISA, okay.

So, such cases, say take off at ISA sea level, that's what is been preferred as a cycle design point, okay. So, selection of mass flow rate, that's what is very important and that is the reason why we have introduced the parameter, that's what is corrected mass flow rate. So, you must realize what is the reason why we are having these corrected parameters, okay.

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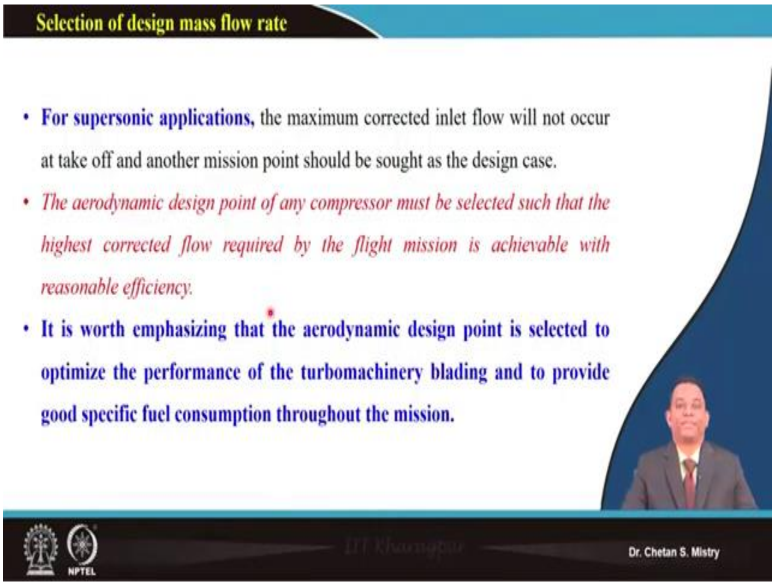

At the same time, suppose if I am talking about application for say your military purpose, where we are looking for say supersonic flights, you must realize under that condition your corrected mass flow rate that may not be happening at the take-off condition because your maximum thrust requirement that's what will be depending on which kind of manoeuvre you are doing, at what flight Mach number you are flying, okay. So, under that condition, it is very crucial to select the mass flow rate.

And it says for aerodynamic design point, the compressor must say any compressor must be selected in such that highest mass flow condition that's what will be achieved at say flight mission requirement with reasonable efficiency, okay. And it is worth emphasizing that aerodynamic design point is selected to optimize the performance of turbomachinery blading and to provide good specific fuel consumption throughout the mission.

So, we must realize, what we are selecting as say corrected mass flow rate for both our engines say commercial aircraft or say your fighter aircraft, this mass flow rate, they are different, okay. Mostly for fighter aircrafts, people, they are considering say where they are having maximum mass flow rate condition or maximum thrust required condition, that's what is conventionally been say selected.

That's what has been verified also for say take off condition, few percentage variations that's what will be there and according to the experience and based on database available with aero engine companies, they people, they are selecting this mass flow rate condition. So, many times, when students they are doing their design for say fighter aircraft, conventionally they are considering say supersonic cruise condition as say mass flow rate condition or corrected mass flow rate condition, okay.

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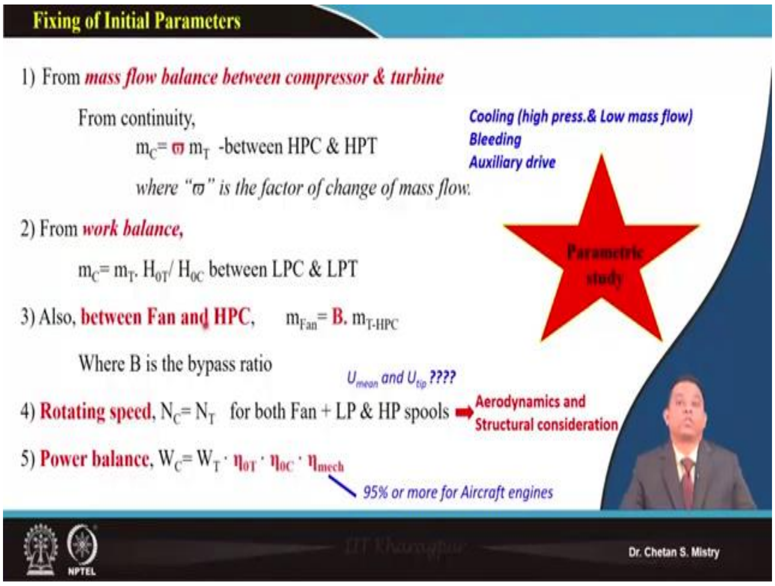

Now, when we realize what we are talking about the mass flow rate, very next step, that's what will be coming is the fixing of our initial parameters. What we say initial parameters, very first parameter we can say, we need to have balance of say mass flow rate for compressors and turbines. What it says from our continuity, my mass flow rate through the compressor that's what is given by say this is what is my say factor, that's what is representing change in mass flow rate and this is what is represented mass flow rate through my turbine.

$$From\ continuity,$$

$$m_c = \varpi\, m_T$$

$$where\ "\varpi"\ is\ the factor\ of\ change\ of\ mass\ flow$$

So, this equation, that's what we are applying mass balance we are applying for HP compressor and HP turbine. The reason here, you can understand the mass flow rate, that's what is going inside my turbine that's what will be slightly different. The reason here is say some of the air or fraction of air, that's what we are using say highly compressed air with slightly high temperature that's what we are injecting at say turbine, say HP turbine, for cooling purpose, okay. So, some fraction may be 2 to 5% of air that's what they are using for the cooling purpose.

Some special applications for say your commercial aircraft, some amount of air that's what has been taken for bleeding purpose. So, basically when we are flying at high altitude within your aircraft, the pressure, that's what will be falling down and in order to maintain the cabin pressure, we are using this bleeding air, that's what we are coming…that's what is coming out from your high-pressure compressor, okay.

Now, some of the applications, we can say, that's what is used for say driving auxiliary devices. If we consider, say we are having many pneumatic systems…say, if we consider…say…for wing, we look…we are looking for say movement of that wing for say breaking purpose, we are using that for lifting purpose; so, that's what is required say kind of compressed air.

Sometimes for landing gear actuation also, this kind of mechanism, that's what has been used. So, basically for control mechanisms actuation, we are using the compressed air and that's what we are taking from high pressure compressor. So, when we are doing our design, we need to be very careful by what percentage we are extracting or we are taking out the air from HP compressor and that's what is basically will be going to say, by reduce amount, it will be going to your HP turbine, okay.

Next, that's what is we need to do our work balance. Suppose if we consider say for our LP compressor and your LP turbine; so, we need to balance that in sense of our energy equation, okay. So, this is what is basically we need to realize what power that will be generated by our turbine, that's what will be used to rotate our compressor.

$$From\ work\ balance,$$

$$m_C = m_T \cdot H_{0T}/H_{0C}$$

If we consider say for LP configuration, my LP turbine that will be rotating say my LP compressor and suppose if we consider for two-spool configuration, my HP turbine that will be used to rotate say HP compressor. So, here in this case this work balance, that's what is very important, okay.

Now, if we consider we are having say high bypass ratio or low bypass ratio configuration, under that condition, we will be having the parameter that's what is called bypass ratio. So, mass flow rate through my fan, that's what will be given by bypass ratio and mass flow rate that's what is going through my HP compressor. We can say this is what is going to my core engine, it depends what kind of configuration we are selecting with, okay.

$$Between\ Fan\ and\ HPC,$$

$$m_{Fan} = B \cdot m_{T-HPC}$$

$$where, B\ is\ the\ bypass\ ratio$$

So, this bypass ratio that also must be known to us or we need to decide. So, basically all these parameters, they are parametrically you need to initially guess with and later on you need to fix those parameters as per the expectation of your engine or as per your requirement of the engine.

Next parameter we will see, that's what is in sense of say your rotational speed. So, as we have discussed my rotational speed of the compressor and my rotational speed of the turbine that need to be same. Now, here in this case, major challenge that's what will be coming when we are talking about say your LP compressor or say fan where we are having limitations in sense of aerodynamics and in sense of my structure, so this point we have discussed earlier also.

So, basically, we need to keep on eye what will be my mean peripheral speed and what will be my tip peripheral speed. So, mainly when we are discussing about the fan, there may be chances because of larger diameter though it is having low rotational speed, but it is having larger diameter, my flow will go transonic near the tip region and that may lead to reduce say your efficiency and that is the reason why you need to keep on eye when we are selecting these numbers, okay.

$$Rotating\ speed,$$

$$N_C = N_T$$

$$For\ both\ Fan + LP\ \&\ HP\ spools$$

Now, when we are doing our power balance, say for compressor and turbine, let it be LP compressor, let it be say HP compressor, we need to do the balance in this sense. So here, this is what is representing my turbine efficiency, my compressor efficiency and this is what is my mechanical efficiency. So, conventionally for aero engines the mechanical efficiency is assumed to be on higher side, you can say this is what is roughly in the range of more than 95%, okay and that's what is making these aero engines more expensive and more focused compared to other devices.

$$W_C = W_T \cdot \eta_{0T} \cdot \eta_{0C} \cdot \eta_{mech}$$

Now, here in this case, we need to consider, say next is in sense of going with the parametric studies. So, what all we are discussing here, that's what need to be initially guess with then we need to go with the cycle analysis; based on that cycle analysis we will be calculating what we are looking for at the end in sense of thrust as well as in sense of specific fuel consumption.

So, when we say our thrust and specific fuel consumption they are not meeting then we need to go with the systematic parametric study. So, as we have discussed, these gas turbine engines basically all these parameters, they are been initially designed with based on cycle analysis. So, for engine manufacturing companies they are having their in-house code, in-house design codes with which they are selecting or they are designing this engine.

There are commercial codes also available which students can use or maybe new start-up companies can use in order to do the cycle analysis. So, you know optimization or the parametric study of all this parameter that's what is very important, okay. These all parameters they are of great importance to us, okay.

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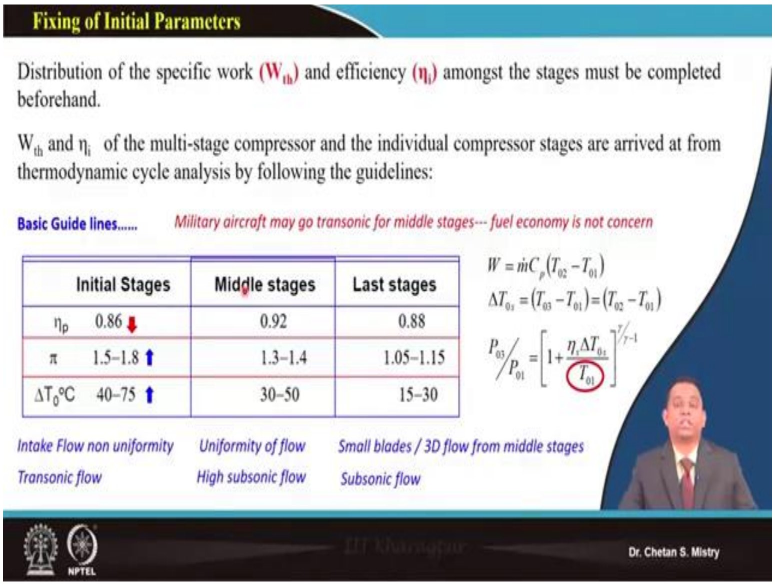

Now, let us say, when we are saying…say, fixing of our initial parameter then two parameters they are of great interest; that's what is my specific work and second parameter, that's what is my efficiency, okay. So, when we are saying these two parameters, work done and my efficiency for individual compressor, so when we are doing our cycle analysis that time we need to put some numbers, say some assumptions we need to do in sense of efficiency, okay.

Now, these guidelines what we are discussing at this moment that's what is very important and that need to be realized at the very beginning stage only. You cannot select these numbers randomly. And there is a logic, systematic logic behind selection of these numbers. So, if we consider, we are having say initial stage; so, if you consider we are having say LP compressor or maybe we are having fan or say we are having booster stage for that polytropic efficiency per stage you can assume safely to be 86%, okay.

And my pressure ratio we can select in the range of 1.5 to 1.8 and it says my ΔT_0, that's what is in the range of 40° to 75°. Now, the question may arise; Sir, why this number that's what is say lower? Basically, this is what is my initial stage. We can realize, the flow that's what is entering inside my compressor that may be having some kind of flow non-uniformity, okay. And this flow non-uniformities that may lead to reduce my performance or my efficiency.

One more thing is when we are talking about the initial stage, we can say, we are having our entry temperature to be lower compared to other stages. If this is what is your case, there may be possibility that my flow will be going transonic in that range, okay. When it is going transonic, we must realized, we are having losses to be large, my aerodynamic losses will be increased. When my aerodynamic losses are increasing, my efficiency will go down, okay; and that is the reason why we are assuming this initial efficiency to be 86%.

Now, when we are talking about the pressure ratio, it says this is what is higher, basically when we will be discussing our transonic compressors, that time you will realized, we are taking the benefit of what shock formation, that's what is happening and that shock formation within the blade passage, that's what will be helping us to achieve high pressure ratio and that's what is a trend. And, that is the reason if you are looking at my pressure ratio expected from the initial stage, that's what will be larger.

So, here my pressure ratio will be larger for the initial stage. If we consider say for our middle stage, so here, our efficiency is coming to be larger, okay; we are assuming or we need to assume this number to be larger. It is not because we are assuming the number it has a reason, reason is we will be having more uniform kind of flow that's what is flowing and my flow that's what is say high subsonic kind of configuration and that's what is having benefit in sense of aerodynamics, okay.

So, my blade aerodynamics, that's what is supporting here and it says we can safely assume our efficiency in the range of 91, 93%, okay. And pressure ratio that will be in the range of 1.3 to 1.4. My temperature ratio, that's what we can safely assume between 30 to 50 degree, okay. So, middle stage, that's what is having higher efficiency. You can say later stages of my LP or my initial stage of HP can be of this configuration, okay.

Now, last stages, we can say HP compressor large stages, for that our efficiency we are assuming to be 88% and our expected pressure ratio that is also on the lower side, it may be say 1.05 to 1.15 and my temperature rise expected that is also between 15 to 30. The reason here is on later stages or on the rear side our blades are smaller blades that's what is not because we are selecting this blade to be smaller one this is what is because of specific reason, we are having our continuity need to be satisfied.

And as we have discussed, because my blades are lower height and that is the reason we will be having the flow three dimensionality that will be coming into the picture. And if this is what is your case, you will be having the loss of efficiency and that is the reason why we are not expecting high pressure ratio and even we are not expecting higher efficiency.

For such kind of flows, we are having our flow to these airfoils or say to these blades, they are mainly subsonic, okay. So, what all we are discussing, that's what is giving us guideline how do we decide with our pressure ratio, okay. Suppose if you are talking about application or say design of axial flow compressor for military purpose, under that consideration, we are expecting number of blades or number of stages to be lower because we are having special requirement.

So, middle stages they are also going transonic, because there we are not having fuel consumption or say my fuel economy as a major concern. So, based on the requirement, based on our expectation, we need to select with. So, if you look at, we are designing suppose say high bypass ratio turbo fan engine or say low bypass ratio turbo fan engine for commercial application, this is what will be giving you rough estimation for the initial starting.

Later on based on your calculation, we will see, we will discuss in later part, that based on our expectations we can go with the change in my numbers for pressure ratio, okay. Suppose say, if we are considering high pressure ratio, overall pressure ratio requirement, that's what will be increasing my number of stages. Then under that condition in order to reduce the number of stages, we will be going with say increasing the pressure ratio…per stage pressure ratio. So, they all are the tricks and tactics which are been implemented for aero engines.

So, this is what is all we are discussing at this moment for say design of axial flow compressor. We have started discussing about the selection of parameters and then we have started discussing about the very important parameter that's what is say our mass flow rate or corrected mass flow rate for the initial guess or initial starting point or design point. Then we are discussing about say how do we decide with the pressure ratio for individual stage. Thank you very much, we will continue our discussion in next lecture.