Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture 49
Transonic Compressors

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Hello, and welcome to lecture 49. From today, we will be start discussing about the Transonic Compressors.

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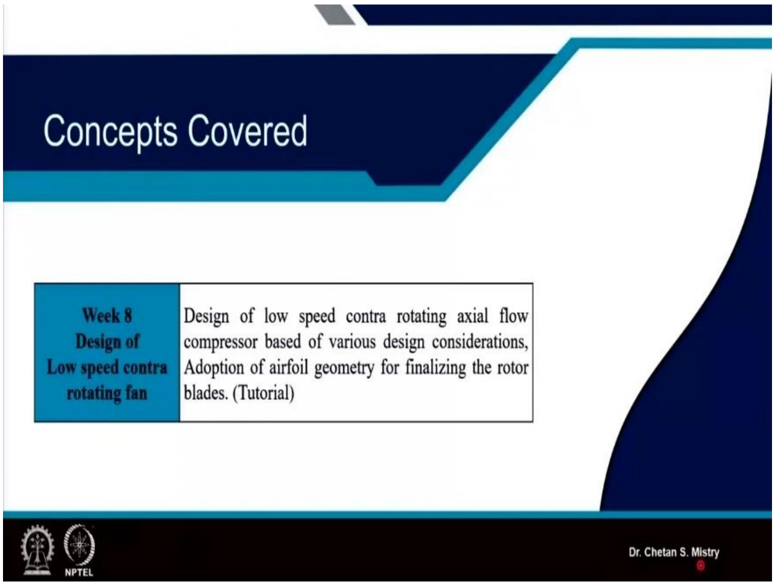

So, in last session, we were discussing about the design of low speed contra rotating fan. We have taken a design using two design approaches for say contra rotating fan. One, that's what is by using fundamental design approach and second, that's what is by using free vortex design concept. And we realize, like, what all are the change because of selection of different design approaches or whirl distribution approaches. What we realize is say, when we are opting for say free vortex concept for which we will be having our blades to be highly twisted both for rotor 1 as well as for rotor 2.

At the same time, because of fundamental design approach where we having great control in sense of parameters, we can make a blade less twisted and that's what will be giving say operating range to be wider that's what is expected to be. Secondly, the manufacturing, that will be easy when we are going with the fundamental design approach. It is not always that you will be going with these two design methodologies only. You can go with other design approaches also. You can go with force vortex designed. You can go with say constant alpha design concept, okay. So, these all we can do once we are having fundamental understanding of contra rotating fan.

Now, from today we will be discussing about the transonic compressors. Before going into detail, the question may arise in our mind why, what and how. In sense, why we are going for transonic compressors, what all are the benefits we are getting by opting with the transonic compressors, how to achieve what all we are looking for in sense of having say compression system design. Let it be applicable for say land base powerplant or say aircraft powerplant. Now, this all we will be covering in this week, okay.

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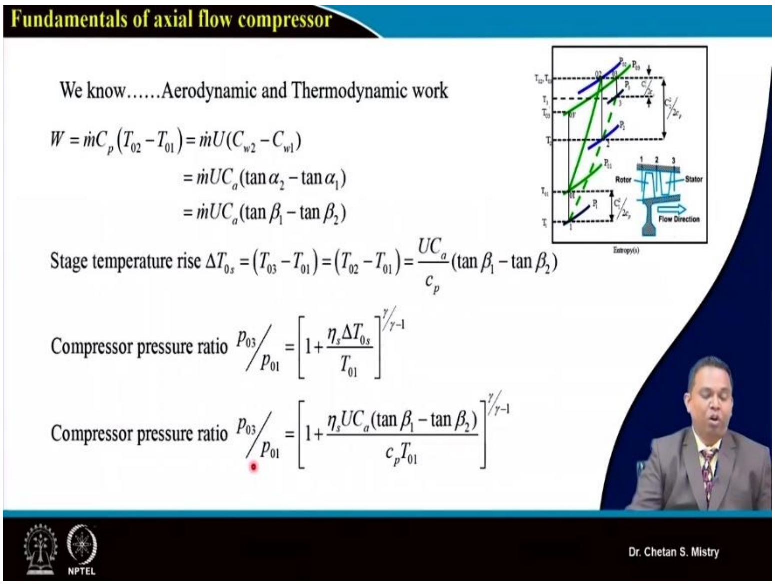

Now, let us move with what all we know in sense of our fundamentals. What we know? We have our compression work, that's what you can be represented in sense of thermodynamic or the temperature term as say $\dot{m}C_p\Delta T_0$. And we can equate that as aerodynamic work because we have realized our thermodynamic work and aerodynamic work that needs to be same. So, if we are putting this both this to be same, we will be getting my stage temperature rise, that's what can be given as say $\frac{UC_a}{C_p}(\tan\beta_1 - \tan\beta_2)$.

$$W = \dot{m}C_p(T_{02} - T_{01}) = \dot{m}U(C_{w2} - C_{w1})$$

$$= \dot{m}UC_a(\tan\alpha_2 - \tan\alpha_1)$$

$$= \dot{m}UC_a(\tan\beta_1 - \tan\beta_2)$$

We are more interested in say our compression ratio. So, compression ratio, that's what we are correlating in sense of ΔT_0 and our isentropic efficiency. So, in overall, if I will be putting my compression ratio, we can say this is what will be the formula. This is what all we have discussed during our second week session.

$$Stage\ temperature\ rise\ \Delta T_{0s} = (T_{03} - T_{01}) = (T_{02} - T_{01}) = \frac{UC_a}{C_p}(\tan\beta_1 - \tan\beta_2)$$

$$Compressor\ pressure\ ratio\ {}^{p_{03}}/_{p_{01}} = \left[1 + \frac{\eta_s \Delta T_{0s}}{T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$$

$$Compressor\ pressure\ ratio\ {}^{p_{03}}/_{p_{01}} = \left[1 + \frac{\eta_s UC_a(\tan\beta_1 - \tan\beta_2)}{C_p T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$$

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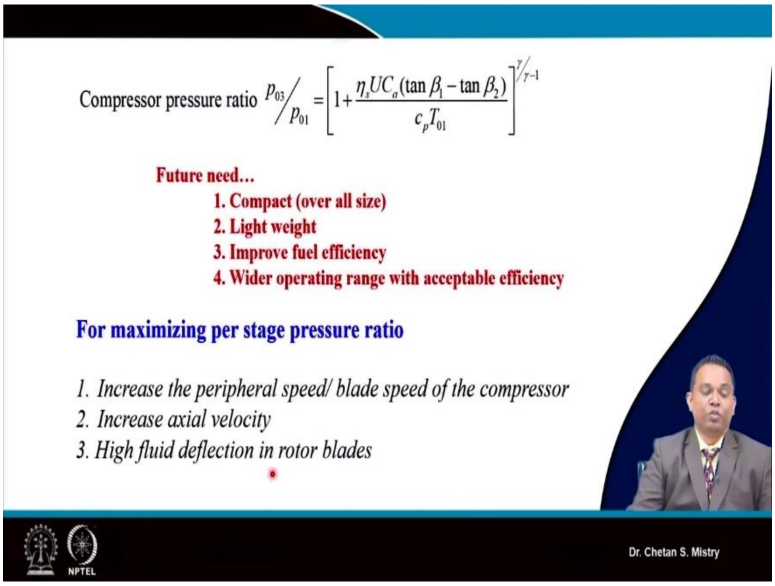

So, we can say my compression ratio for the compressor, my axial flow compressor, that's what is a function of efficiency, my peripheral speed, axial velocity and we can say $\beta_1 and\ \beta_2$. That's what we can represent as say $\Delta\beta$ that we can say…it is…say deflection angle or we can say my change of $\Delta\beta$ or say…we can say what is the change in my blade angles, okay?

$$Compressor\ pressure\ ratio\ {p_{03}}/{p_{01}} = \left[1 + \frac{\eta_s U C_a(\tan\beta_1 - \tan\beta_2)}{C_p T_{01}}\right]^{\frac{\gamma}{\gamma-1}}$$

Now, what is our expectation, what all we are looking for? Say, we are looking for future compression system that need to be compact.

When we say compact, that means overall size need to be lower. We are looking for the engines, that's what need to be lightweight. We are looking for the engines which are having say fuel economy. Now, when we are reducing the size and weight of the engine, we can say basically we are reducing the drag. The drag of the engine that will be reducing in overall sense that's what will be helping us in sense of improving our fuel economy, okay. These days, people, they started talking about wider operating range and, you know, with acceptable efficiencies.

We can say now acceptable efficiencies for compressor, that's what is ranging from 88% to 92%. Thanks to the development of technology, thanks to the development of computational tools, thanks to say instrumentation, experimental facilities and much more mature understanding of design, okay. Now, when we are talking about all this as expectation that means, what we are looking for is we are looking for per stage pressure rise to be large. When we say when we are having per stage pressure rise to be higher, we can say we are able to reduce the number of stages that means we are able to achieve the compactness.

When we say we are reducing the number of stages for the compressor, we are basically reducing the weight of the engine that means, we are basically reducing the drag and that’s what will be helping incense of our fuel economy. So, what is our requirement is we are looking for maximizing our compression ratio.

Now, from this formula we can say, fundamentally in order to achieve high compression ratio, we are able to achieve by increasing our peripheral speed or by blade speed of the compressor. Secondly, we can increase the axial velocity. Third, we will be having say high flow deflection angle for the rotor blades. So, by having the variation in these three parameters, we are able to achieve the higher compression ratio.

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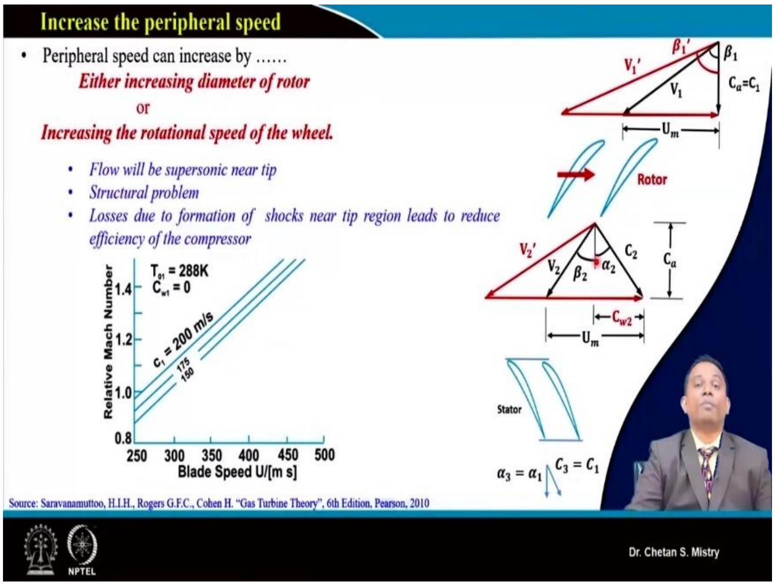

Now, let us try to understand one by one. Say, this is what all we have discussed earlier. But the today’s approach for understanding that’s what will be different. Now, let us see we are opting for the first option, that’s what it says increase the peripheral speed, okay. We can say if you are looking for increasing the peripheral speed, we have two options either we can increase the rotational speed or we can increase the diameter, okay, or we can say, we can increase the span of my blade. Now in order to understand that part, let us see if we are considering we are increasing our rotational speed what will happen; because of increase of our rotational speed, my relative velocity, that’s what is going to be higher.

At the same time, we will be having our β_1' that's what will be coming to be higher. If this flow, that's what will be incident on say my rotor blade at the exit also we will be having our relative velocity coming to be larger, okay. Here in this case, we are assuming our axial velocity to be constant, okay. Now, this is what all we are discussing, when we are increasing our peripheral speed or we are increasing our diameter. Suppose say this red color one, that's what is modified velocity triangle at the mid station. We can say when we are moving towards the tip, this velocity triangle that will be modified in such a way that we will be having relative velocity component to be very large.

When we say our relative velocity component, that's what is coming to be large that means my flow will be going supersonic near the tip region, okay. When we say it is going supersonic near the tip region; secondly, we will be having say the problem that's what is related with the structure. Because my aerodynamic loading in that particular region, that's what is going to be change, okay.

If we consider say our blade, that's what is fixed near the hub and it is free…at the free end near the casing, that's what is acting like a cantilever beam. And, that's what will be subjected to say aeroelasticity problem. So, we can say we are having two difficulties when we are increasing our rotational speed. First, that's what is my flow will be going supersonic. When I say my flow is going supersonic, that's what will be inviting the formation of shock, okay. And we know this formation of shock near the tip region, that's what will lead to increase the irreversibility in the flow. That means that's what is going to increase the losses.

When we say we are increasing the losses, our aerodynamic losses, that's what is going to be increased that means it gives the penalty in sense of efficiency to be reduced, okay. And secondly, we can say that's what is with the say aeroelasticity problem. Now, you know, our demand is moving towards high per stage pressure ratio, that means, we cannot stick with what all we are discussing at this moment. That means, the research and development activities needs to be carried out. So, this was a thought process during 50s and 60s.

Later on, people they realize, in order to achieve the goals, we need to think our design methodology, our design activity need to be understand in a different way. Suppose we say there is a formation of shock, why do not we think of opting the benefit, that's what we are getting from the shocks. And that's what has given new innovative idea for the development of transonic compressors, okay. Here in this case, if we are looking at this is what is a representation we can say, if you are increasing our say blade speed, for particular absolute velocity, we will be having our relative Mach number that's what is going to be increased, okay.

That means, when we are opting with say higher…say…peripheral speed, we need to go with say higher Mach number, there is no alternative to that, okay. Now, we need to find the solution for such kind of problem. Let us move with the second option.

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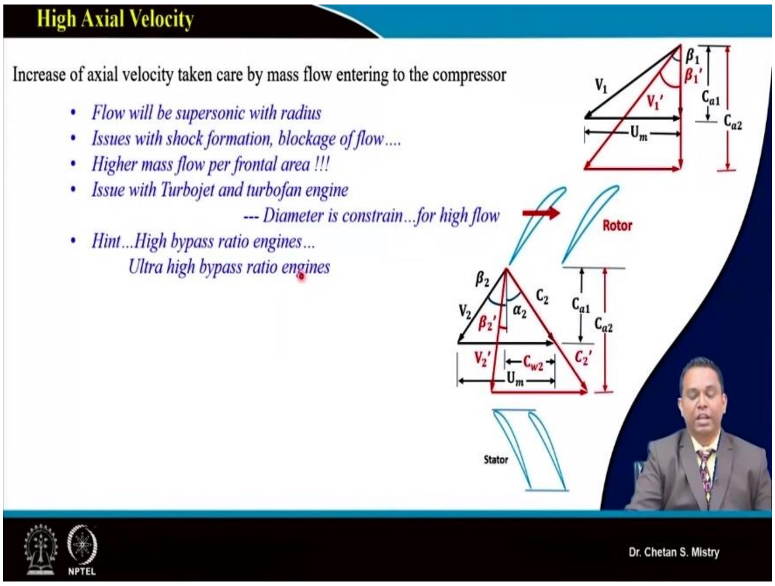

So, second option what it says like we can increase the axial velocity. Suppose if I consider this is what is my velocity triangle, for that velocity triangle, let us increase the axial velocity. When we are increasing our axial velocity in line to what all we have discussed for say higher rotational speed or say higher peripheral speed, we are getting our relative velocity component to be large; that means again, here my flow will be subjected to supersonic condition, okay. So, flow will be supersonic with the radius, okay.

It gives the problem in sense of shock formation, my blockage of the flow, those all difficulties, that's what will be coming into the picture. Now, as we discussed, like, we need to find a solution for this problem. Secondly, when we say, we correlate our axial velocity with the mass flow rate, when we say we want to increase our axial velocity that means we need to increase the mass flow rate. This high mass flow rate, that's what is demanding for higher frontal area. Basically, this is nothing but the engine swallowing capacity, okay.

Now, there are engines which we are fitting for say military engines, basically my dimension that's what is the constraint. So, you know, when we are having our diameter, that's what is a constraint, we cannot go with this option. But that's what is not the problem say for commercial engines, say high bypass ratio engine or ultra high bypass ratio engine, these innovations that's what has come from this idea of increasing the axial velocity, okay. So, we need to start finding the solution for this kind of problems.

Again, here also we are saying, we are having difficulty with the shock formation, the shock formation, that's what is acting like a blockage to my flow and that's what will lead to increase the losses and that is giving the penalty in sense of efficiency.

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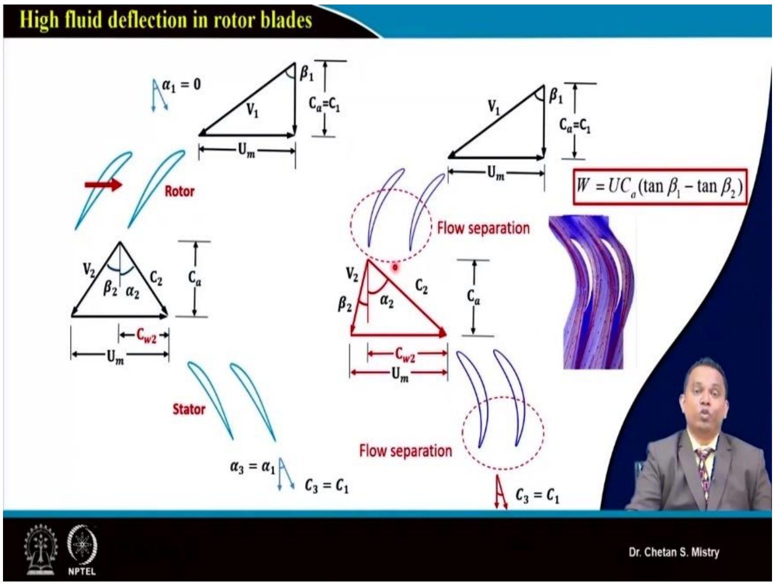

Now, if we go with say the next option, that's what is with say change of my deflection angle. So, here on left hand side, if we are looking at, this is what is representing say conventional stage. Now, when we are looking for say higher aerodynamic loading, in order to achieve high pressure ratio, we can understand what we need to do is; in order to achieve higher diffusion, my inlet relative velocity and outlet relative velocity that need to be managed. Managed in the sense, at the exit my relative velocity component need to be lower.

In order to achieve that, we need to have our blade, that's what is highly cambered blade. So, here if you look at, these blades are higher cambered compared to what all we are having earlier, okay. Now, what is happening when we are decreasing our relative velocity that means we are doing our efficient diffusion. At the same time, based on our fundamental we can say, my absolute velocity is going to be higher, that means we can say the velocity with which my flow that's what will be entering inside the stator, that's what is larger.

There also we are looking for say diffusion to happen. Be careful, here for the rotor, we are having rotational speed that's what will be helping us for doing the diffusion. Here, this is what is a stationary action, okay. So, it may be possible that my flow, that's what will be going to be, you know, at higher absolute velocity with higher kinetic energy and you need to diffuse that efficiently. In order to do such kind of diffusion, we are looking for say highly twisted blade or we can say highly cambered blade. So, here this stator also will be having higher camber. Now, when we say we are having highly cambered blade, since we are working or operating under adverse pressure gradient, there are more chances for my flow to get separated, okay.

My flow will be getting separated maybe from suction surface or maybe from the pressure surface based on my flow condition; this is what all we have discussed earlier also. Here in this case my flow will be getting suppose say separated from suction surface; here also, suppose it will be getting separated from the suction surface.

Now, we need to find alternative which will be helping us in sense of reducing the possibility for say, you know, flow separation and as the reason we have discussed, people, they are opting with say different methodology, that's what is say tandem configuration, somewhere, people, they are going with say slots with the suction in order to avoid such kind of situations. So, you know, with problems we always need to find a solution for that, okay.

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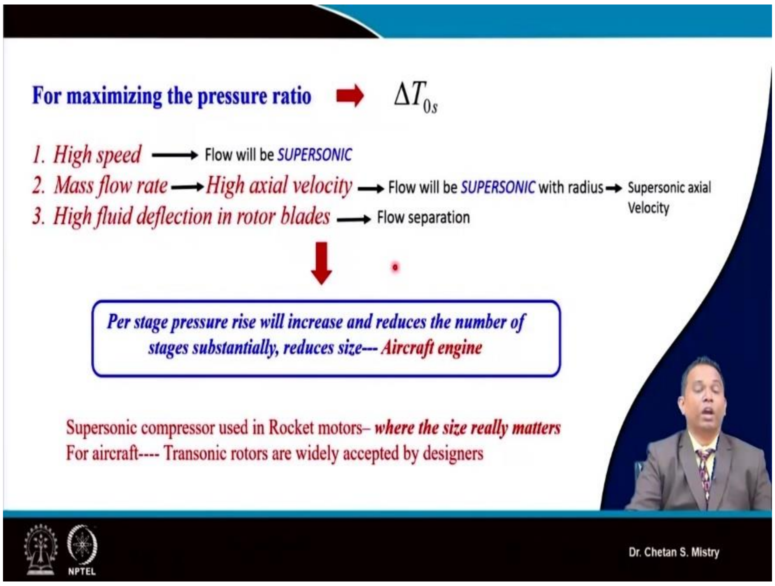

Now, again let us come to the point. What it says? We are looking for maximizing our pressure ratio that means we are looking for higher ΔT_0. Now, in order to achieve these higher ΔT_0, we are going with the higher rotational speed. There we are having difficulty with the supersonic flow. When we are going with say higher mass flow rate or higher axial velocity, that is again we are having say difficulty with the supersonic flow, okay. And, higher deflection, that's what will be giving us difficulty in sense of flow separation. What we are looking for? We are looking for per stage pressure rise to be higher.

In order to reduce the number of stages, in order to reduce the size of the engine, in order to reduce the weight of the engine, in order to improve the fuel economy for future Aero Engines, okay.

Now, these supersonic compressors they are mainly been used for rocket motors, where the size is really a constraint. For aircraft, people, they started opting with say these transonic compressors. So, that is the reason why we will be discussing the design methodology and design approaches for transonic compressor. But before going into the design concept, we need to understand what all are the difference between subsonic and say transonic compressors, okay.

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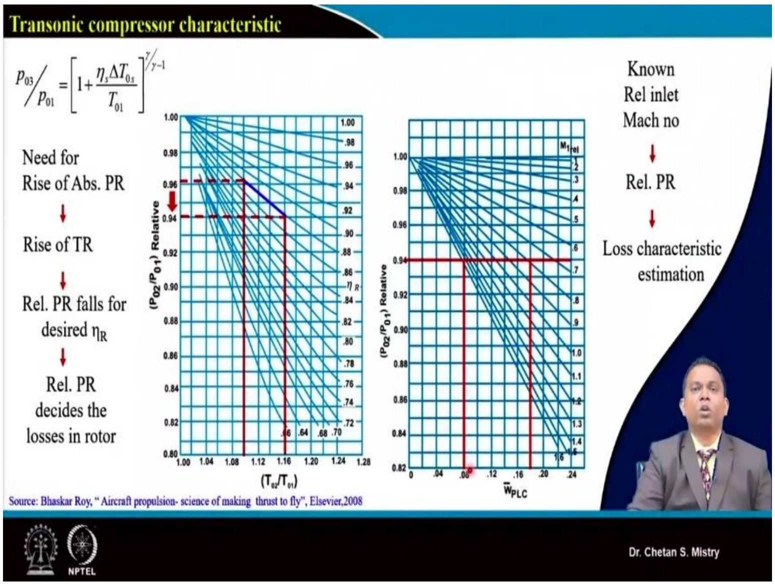

Now, let us see. Say, this is what is a representation for what all we are discussing. Say, we are looking for our high pressure ratio, per state pressure ratio. What it says? We are looking for my ΔT_0 to be larger. Suppose if we are considering, say my ΔT_0 we are looking for to be larger. If we are going with the same efficiency; suppose here, let us assume I am expecting my efficiency to be 88%. Under that condition, we will be having our relative pressure ratio, that's what is going to be reduced. This relative pressure ratio that is nothing but that's what is representing my pressure rise, that's what is happening inside my rotor, okay.

And, you know, like this relative pressure ratio, that's what will be helping us in sense of understanding what all are the losses which are happening within the rotor. Now, if we consider here, say my relative pressure ratio suppose I am considering as 0.94 and if you are looking at, this is what is representing my relative entry Mach number, this is what is representing my losses. What it says? If we are going with say my relative Mach number to be higher, then we are able to have lower losses.

Suppose if you are going with say flow to be relative Mach number to be lower, my losses are going to increase. That means, in overall sense, everything that's what is asking for moving towards the development of compressor to be supersonic in the nature, okay.

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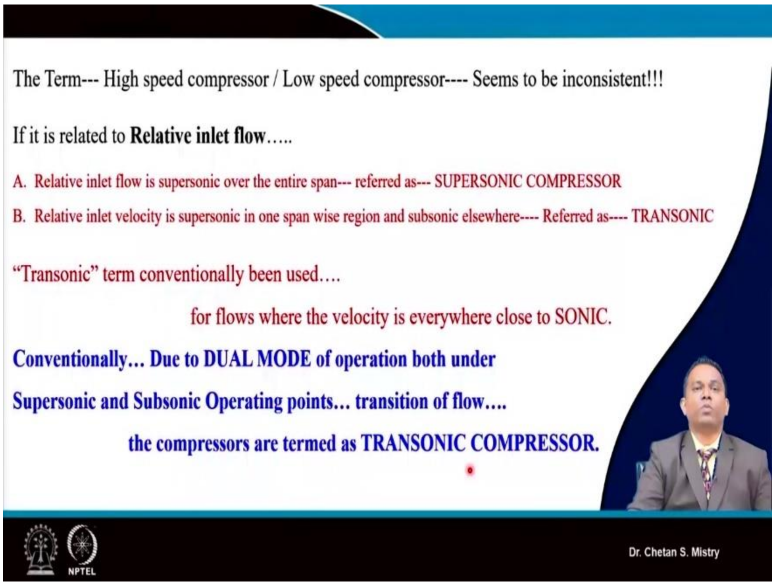

Now, the question, that's what is coming is in sense of understanding for supersonic compressor and transonic compressor, okay. So, the terminology people they were using is say high speed compressor and low speed compressor, that's what is coming to be inconsistent. We can say when we are discussing about the LP compressor, that's what is rotating at the low speed, okay. When we are talking about HP compressor, that's what is rotating at the high speed, okay. So, this low speed and high speed, that's what is a terminology that's what is not coming into the picture when we are discussing about such kind of configuration.

In order to avoid that confusion, we are considering relative inlet flow as a reference. So, if we consider my relative inlet flow is supersonic over the entire span of the blade, that's what is defined as a supersonic compressor. So, throughout my span, if my flow is supersonic, we can say that as a supersonic compressor. My relative inlet velocity is supersonic in say particular span region, okay; and in a remaining region, if it is subsonic then we can say that as a transonic compressor. So, do not get confused in sense of understanding for supersonic compressor and transonic compressor.

Basically, this transonic term, that's what is conventionally been used when we are having our flow very near to say sonic condition, okay. Now, there are different approaches for discussing and understanding the transonic compressor term. But conventionally what we say, we are having two modes of operation, say from subsonic to supersonic or maybe from supersonic to subsonic and that's what is with the operating points, okay. And we will be having the transition of flow, that's what is happening within the blade passage. And that is the reason why we are defining these compressors to be transonic compressor.

When we will be move ahead with, we will be discussing what we mean by transition of my flow from subsonic to supersonic or from supersonic to subsonic configuration. But at this moment, you can understand we are having dual mode of operation, that's what is say subsonic to supersonic or from supersonic flow to subsonic flow within the blade passage or along the span. And, as a reason why we are defining this as a transonic compressor.

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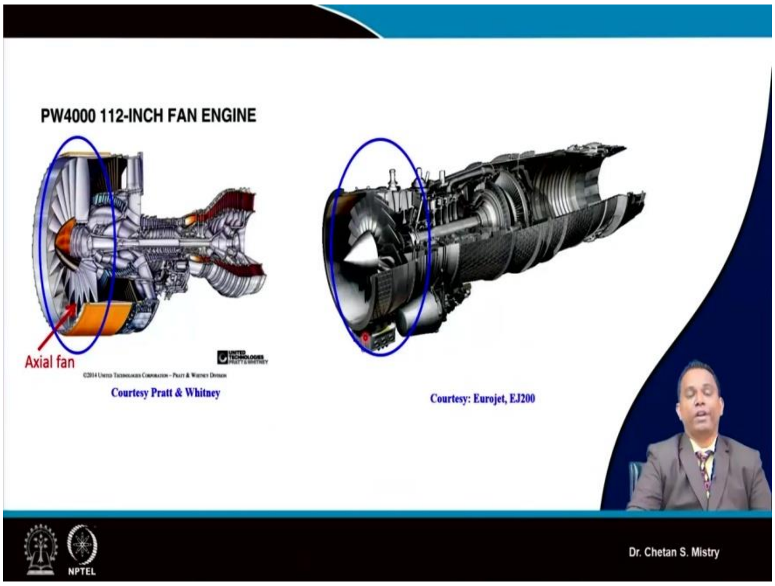

Now, here in this case, if you look at we are having two engines. Say, this is what is high bypass ratio engine and we can say this is what is my fan…axial fan, is a large diameter fan. You can say the diameter of this casing is 112 inch. So, you can understand, this is what is say larger diameter fan. When we have this diameter to be larger, it is prone to happen we will be having flow to be say supersonic near the tip region. And, in the remaining region from say maybe hub to say 70% of my span or 60% of my span my flow will be subsonic. So, here in small region, we will be having say flow to be transonic or we can say it is a supersonic. So, we can say, this fan to be transonic fan, okay.

Now, here this is what is say Eurojet E200. As we have discussed, our expectation is to have the compactness, lightweight. And if we configure this as a special requirement for say military application, under that condition, you are supposed to rotate your fans or LP compressor at high speed. When we say my LP compressor or the fans which are rotating at the high speed, it may be possible that my entire blade, that's what is acting under supersonic condition.

So, that is the reason why suppose say this is what is made up of three stage of fan. All the three stages are of transonic nature, okay. So, you know like for engines, conventionally people, they used to say for high bypass ratio engine fan, that's what is going transonic; for low bypass ratio engine, my LP compressor or the fans, that's what is going to be transonic. Sometimes what happens say maybe for LP compressor or maybe few early stages of HP compressor, they are also of transonic nature.

So, not only for the Aero Engines this transonic flow nature that's what is coming. Now a days with development of technologies and the expectation in sense of say power generation, many land based power plants, they are also having transonic kind of configuration for the compressor, okay.

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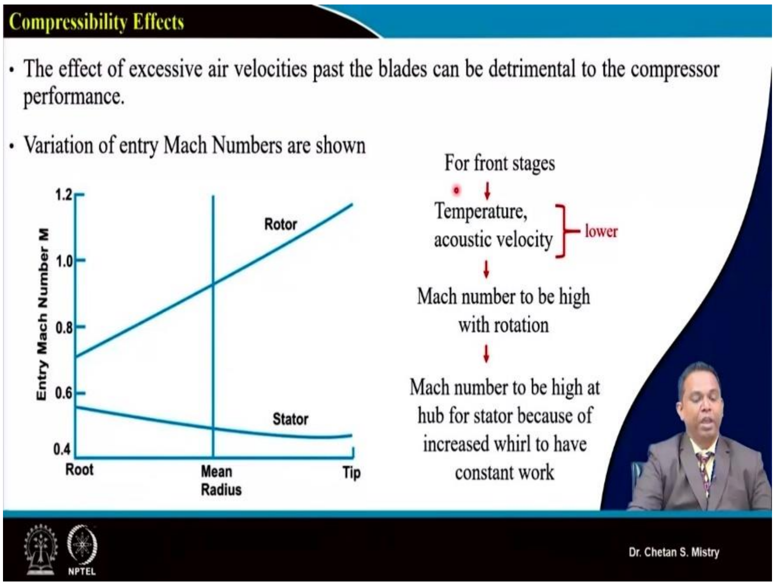

Now, you know, like what all we have discussed my flow, that's what is entering inside my say fan…say…for the front stages, we are having our temperature to be lower and that's what will lead to my Mach number to be higher, okay. And, that's what is giving my flow to be say supersonic in that particular region. This is what is representing the entry Mach number for rotor as well as for say stator. If we compare for the rotor, my entry Mach number, that's what is say lower near the hub region and this is what is higher near the tip region.

And for stator, the reverse configuration we can say, we are having our entry Mach number to be larger. And that's what is because what all we say the constant work loading and the whirl component that's what is coming into the picture, okay. So, this is what is representing how my entry Mach number that's what is varying along my span, along my radius.

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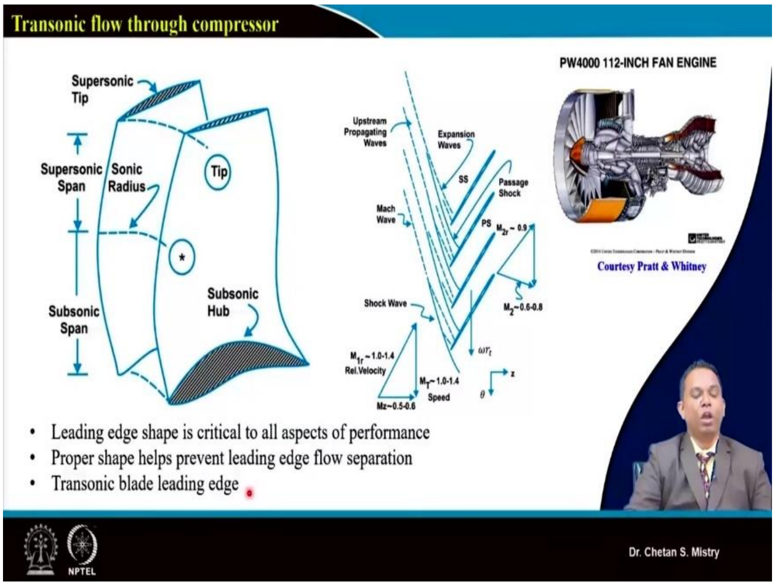

Now, as we have discussed, suppose if you are considering or high bypass ratio engine, so, here this is what is a good representation, we can say up to a certain span, we will be having our flow to be subsonic flow and near the tip region or towards the tip region the flow will be say supersonic flow, okay.

Now, here it is very interesting that we will be having our transition of flow that's what is happening subsonic to supersonic along the span. So, near the hub region, if you look at, my blades are subsonic blades or subsonic airfoils. At the mid station also, maybe we will be having our blades to be subsonic or high subsonic of nature; but near the tip region, my airfoils are of say, you know, supersonic nature. So, these airfoils what we are looking at and this airfoil what we are looking at, these airfoils are different, okay.

Now, you know, my leading edge, that's what is always a critical part when we say flow to be supersonic flow, okay. Now, here in this case, when we have discussed about say low speed compressor or subsonic compressor design, for that we are expecting our leading edge to be, you know, circular one or elliptical one in order to have wider operating range, okay.

Now, if we consider the same kind of say airfoil near the tip region and because of presence of supersonic flow, it may be possible that it will be giving, you know, different flow characteristics, we will be discussing about that part. We know from our fundamentals of gas dynamics, that when we are having our flow to be supersonic, we are looking for the sharp edge. So, here if you look at, this is what is representing in sense of say my Mach number; so, as we have discussed, suppose we are considering our fan that's what is facing the flow, we are looking for entry Mach number to be in the range of 0.4 to 0.5. So, this is what is say in that range and my relative Mach number that's what is coming to be large, okay.

So, this is what is representing my flow to be a supersonic flow that's what is entering inside my flow passage. Now, here in this case, when it is entering because of presence of my leading edge, that's what is say of slightly smaller curvature, that's what is giving the bow shock to be formed. Because of the surface of my suction surface, here we will be having expansion fans to be formed, okay.

We will be discussing the flow structure for this kind of configuration in detail. But at this moment, you can see, my leg…one leg of the shock, that's what is formed, we can say it is a bow shock, that's what is moving away from my blade; and second leg, that's what will be striking on the suction surface of say next coming blade. And this is what is nearly normal shock kind of configuration. Sometimes people used to say this as…say…passage shock, okay. And, this is how my flow that's what will be entering inside.

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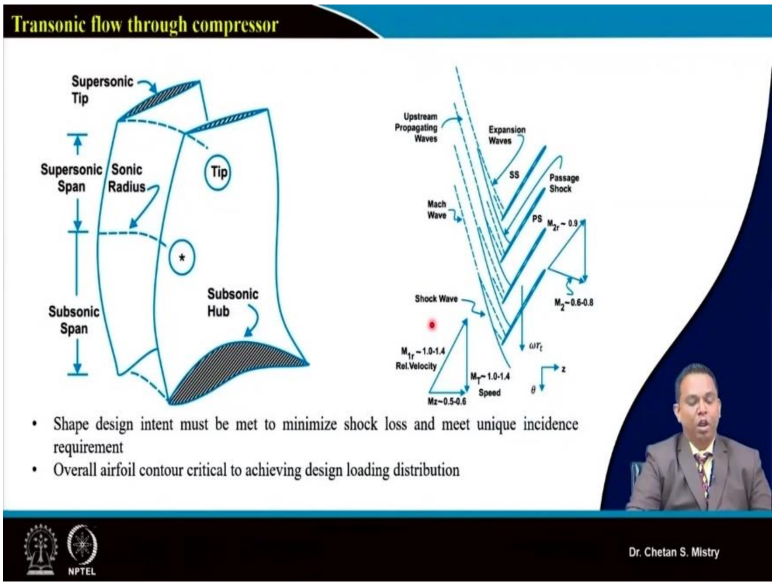

Now, the shape, that's what need to be designed, that's what is very important. So, we will be focusing more, we will be discussing more in sense of what need to be the shape of my leading edge, what need to be the shape of my airfoil for transonic compressor that's what is very important.

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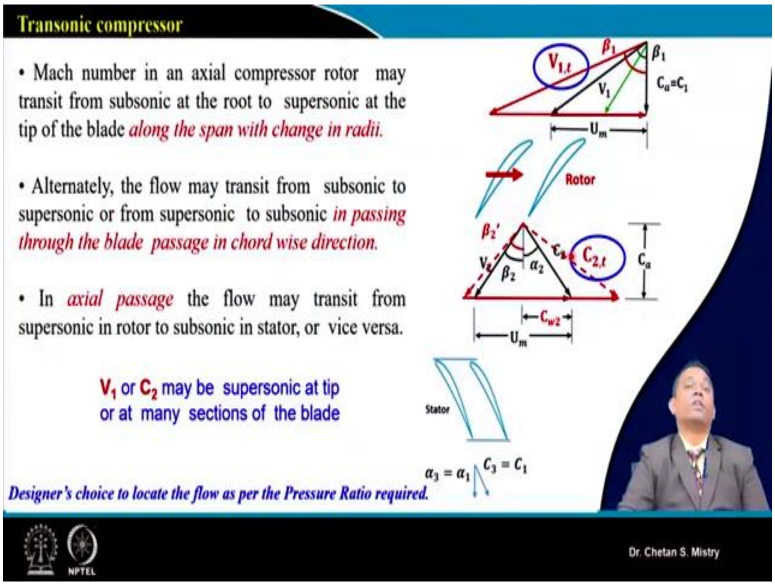

Let us discuss about say what all we were discussing in sense of configuring our compressor to be transonic compressor; what it says my Mach number in axial flow compressor may transit from subsonic at the root to supersonic near the tip region. And that's what is changing along the span with the radius. Secondly, we can say the transition of flow, that's what is happening from subsonic to supersonic or from supersonic to subsonic when it is passing through the blade passage in the chord wise direction.

So, not only what is happening at the front, the flow, that's what is behaving between the blade passage is also equally important, okay. The axial passage flow may transit from supersonic in the rotor to subsonic in the stator and vice versa. Let us try to understand what all we are discussing here in this case. So, this is what is a representation, what we can, my flow, that's what will be going say transonic at the entry of my rotor, okay. So, here we are having say my relative velocity component at the entry of the rotor going to be transonic. It may be possible and we have seen when we are expecting some kind of diffusion to be happened in the rotor, we will be having our absolute velocity coming out from the rotor that also will be having say higher value.

It may be possible that my absolute Mach number that's what will be larger, okay. And, that's what will be giving my flow entering inside the stator also to be supersonic, okay. So, we can say V_1 or C_2 maybe supersonic at the tip or at many sections of the blade. This is what is the designer's choice, what kind of pressure rise he or she is expecting from particular rotor and stator or for the stage, okay.

So, the definition of transonic compressor, that's what is not only based on what is happening at the entry, but you know how to transition, that's what is happening from subsonic to supersonic or from supersonic to subsonic that's what will be defining this compressor to be transonic compressor, okay.

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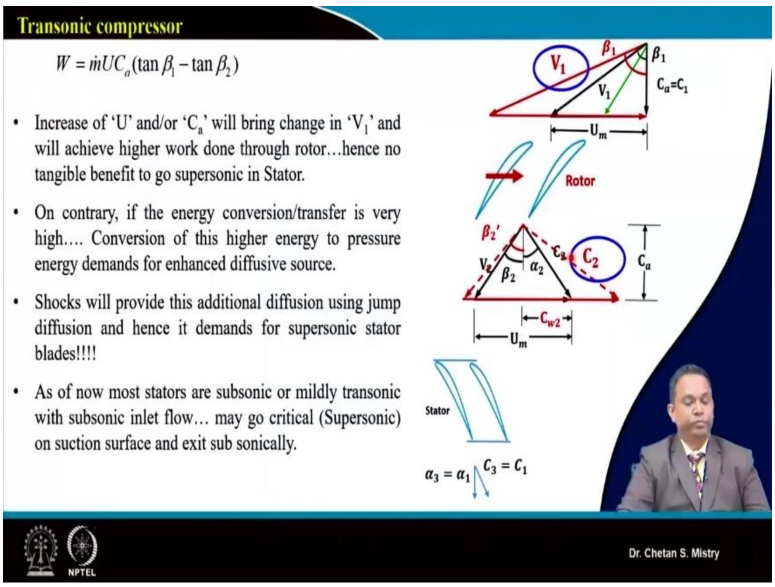

Now, as we have discussed, we can say we are expecting our work done to be larger. Now, when we say are expecting our work done to be larger, what all options we have opted, that's what is say increasing the rotational speed. Suppose say we are increasing our rotational speed, when we are increasing our rotational speed, my flow will be going supersonic at the entry, okay. Now, the flow which is coming out from my rotor, okay, that's what will be having some absolute velocity component.

So, when I am expecting very high diffusion, that's what will be happening from the rotor, as we have discussed, there may be chances that we will be having higher kinetic energy, that's what is coming out from the rotor. Now that higher kinetic energy, that's what is coming out with absolute velocity C_2 that need to be diffused, okay. And in order to have that diffusion to be done, we will be having our stator also to be supersonic, okay.

So, as of now, these stators are subsonic of the nature or say mildly transonic with the subsonic inlet flow, it may go say critical on the suction surface, may be going supersonic on the suction surface but exit as of now, that's what is subsonic, okay. So, this is what all we are discussing in sense of understanding of transonic flow, okay.

With these fundamentals, we will be discussing in detail what all that's what is happening, when we are talking about the transonic flow compressor. Be careful, what all we have discussed up till now, it was subsonic flow, that's what was expected during 50s and 60s and with our expectation with our need; now, we are looking for say compressor stage to be supersonic compressor stage or say transonic compressor stage.

With this we are stopping here. We will be discussing in more detail in the next lecture. Thank you very much for your kind attention. Thank you!