Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture 50
Transonic Compressors (Contd.)

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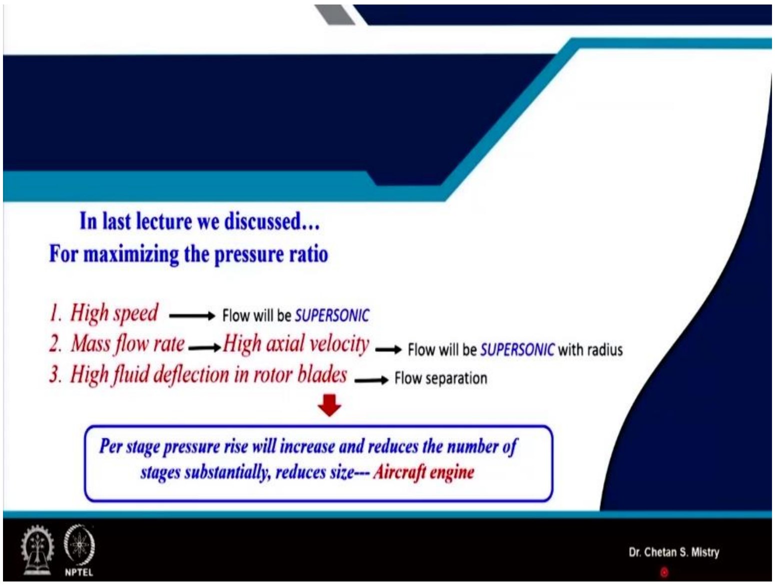

Hello, and welcome to lecture 50. In last lecture, we were discussing our expectation in sense of maximizing the pressure ratio; we can say per stage pressure rise. We have discussed about different possible methods in sense by which we can increase the per stage pressure ratio, one of which it says like we need to go with the higher rotational speed or higher peripheral speed. When we say higher peripheral speed that means, we have option with increasing the diameter or the rotational speed of the compressor, that's what will lead to how flow to be going supersonic in the tip region.

Second option what we have explored, that's what is by changing the mass flow rate or we can say by increasing the axial velocity. When we are increasing the axial velocity at the same time we will be having similar kind of situation near the tip region or at some span region for the blade my flow will be going supersonic. Third option what all we have discussed it, you know, we will be having higher fluid deflection for the rotors and that's what will lead to have the flow separation issue.

So, discussing about first two options; what it says, my flow, that's what is going to be supersonic that's what is of major concern or of interest for these lectures, okay. Now, the situation is, any…by any mean what we are looking for is say per stage pressure rise to be larger or to be higher in order to reduce the number of stages, in order to achieve say compact, lightweight and fuel-efficient engines for the future aircrafts. So, we need to focus our study or our interests more towards the development of per stage pressure rise to be higher. And, as the reason now, we need to address the issues related with the supersonic flow, okay.

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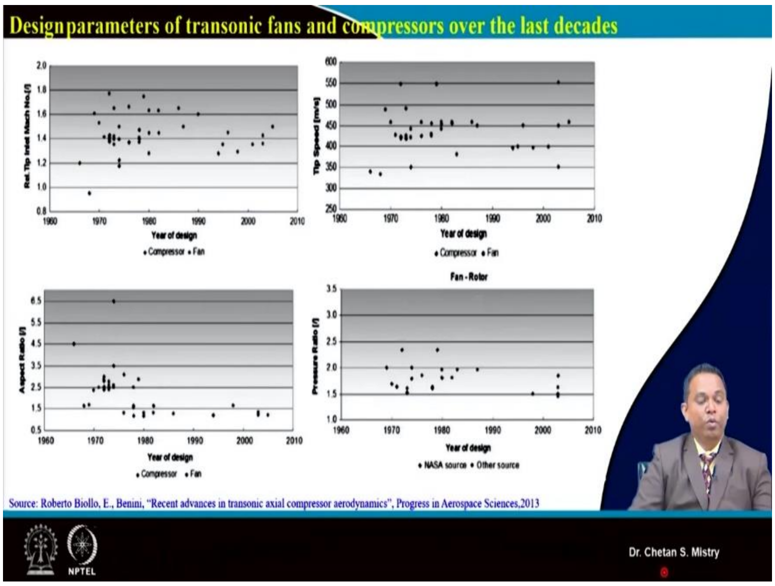

Now, here this is what is representing the trend for say transonic compressors and fans. So, this is what is representing say inlet relative Mach number. So, during 2000, we can see my inlet relative Mach number both for compressor as well as for the fan, that's what is coming to be on a larger side. Same way, when we are looking for tip speed that is also coming to be on the higher side, okay. And, we have discussed the aspect ratio, that's what is having benefits in sense of operating range and efficiency that's what it says aspect ratio is coming to be lower.

So, the interest is towards the development of say axial flow fan and compressor with low aspect ratio with having say higher inlet relative Mach number and higher tip speed, okay. And, expected pressure ratio now, that's what is going to increase because we are looking for the compactness, we are looking for the lightweight, okay. Now, this is what all will be giving idea in sense of how the progress that's what has been happening for this transonic compressor.

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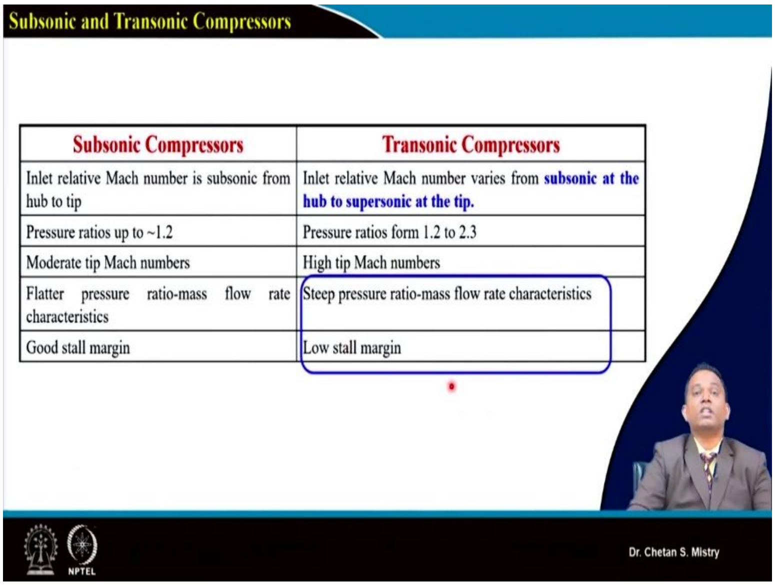

Subsonic Compressors	Transonic Compressors
Inlet relative Mach number is subsonic from hub to tip	Inlet relative Mach number varies from **subsonic at the hub to supersonic at the tip.**
Pressure ratios up to ~1.2	Pressure ratios form 1.2 to 2.3
Moderate tip Mach numbers	High tip Mach numbers
Flatter pressure ratio-mass flow rate characteristics	Steep pressure ratio-mass flow rate characteristics
Good stall margin	Low stall margin

Let us try to understand, like what all we need to understand for say subsonic compressor as well as for say transonic compressor. What it says is my inlet relative Mach number is subsonic when we are discussing about say subsonic compressor, my inlet relative Mach number that's what will be say varying from subsonic at the hub and supersonic near the tip region for transonic compressor. Per stage pressure rise, that's what is expected from subsonic compressor, it is in the range of 1.2.

Now, as we have discussed expected pressure ratio for the transonic compressor it is more than 1.2 to say 2.3. So, this is what is a large range, we can say. My tip Mach number, that's what will be coming to be moderate for subsonic compressor; for transonic compressor, we will be having higher tip Mach number. Now, for subsonic compressor we are having flatter operating characteristic; when we are discussing about the transonic compressor, we are having steeper operating characteristic. We will see what all is the meaning of that. Here, we will be having good stall margin and stall margin for the transonic compressor is coming to be lower.

So, our major interest that's what is we will be understanding what we say as a steeper operating characteristic and low stall margin.

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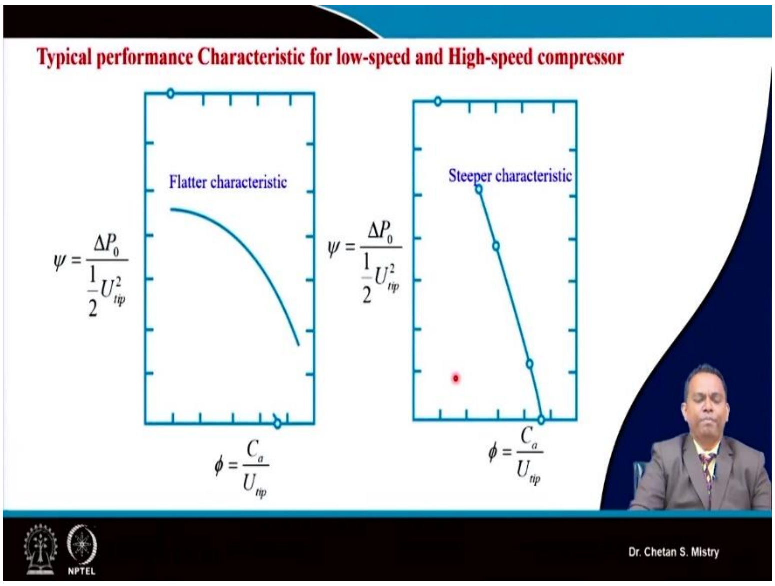

Let us try to look at the performance map when we are discussing about say low speed and high speed compressor. So, this is what is representing per stage pressure ratio in sense of flow coefficient and say, you know, pressure rise coefficient. So, this is what is giving the flatter characteristic, that's what we are achieving by subsonic compressor; and, this is what is representing steeper characteristic, that's what we are achieving by opting with say transonic compressor. So, meaning of flatter and steeper operating characteristic is here, okay. Same way my stall margin for say subsonic compressor, that's what is larger; say my stall margin for transonic subsonic, that's what is lower.

Now, why this is what is happening, that's what is of our interest. So, in next few lectures, we will be discussing about why we are having such kind of operating characteristics, okay!

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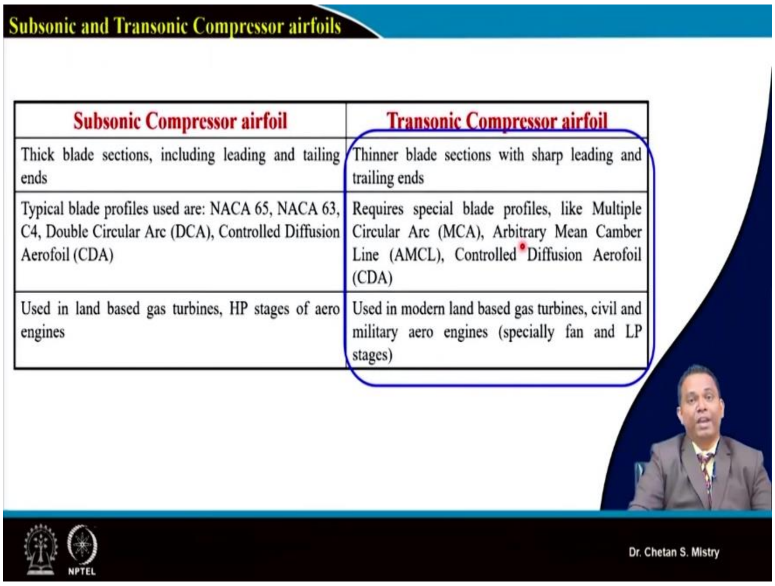

Now, when we are comparing our airfoils, say for subsonic airfoils what we learn over past few weeks that we will be having thicker blades and we will be having say leading edge and trailing edge that's what is having particular shape. When we are discussing about the transonic compressor, it says we will be having our blade or blade airfoils to be thinner one and with sharp leading edge and trailing edge. We are using say C4 airfoil, NACA 65, NACA 63 airfoil, CDA or control diffusion airfoil for say subsonic kind of configuration. When we are moving with the transonic compressor, we are looking for say, you know, double circular arc airfoil, multiple circular arc airfoil, arbitrary mean camber line airfoil, control diffusion airfoils.

We will be having say application of this subsonic configuration, that's what is for say land based power plant, for HP compressor of Aero Engines; but when we are discussing about the transonic, most modern land based power plant for say civil and military engines, specially for fan and LP stage, we are having this transonic compressor. So, now, our major focus, that's what is why we are having this airfoils to be thinner airfoils, why we are looking for say sharp leading edge and trailing edge, why we are looking for special kind of airfoils though we are already having C4 airfoil or NACA 65 airfoil.

We are having different configurations here and there are special applications the reason why we are talking about say transonic compressor, that's what is of application, okay. So, now, we will be discussing about what all we are saying in sense of operating or operating characteristics and what all will be the airfoils and why these airfoils, that's what are different, okay.

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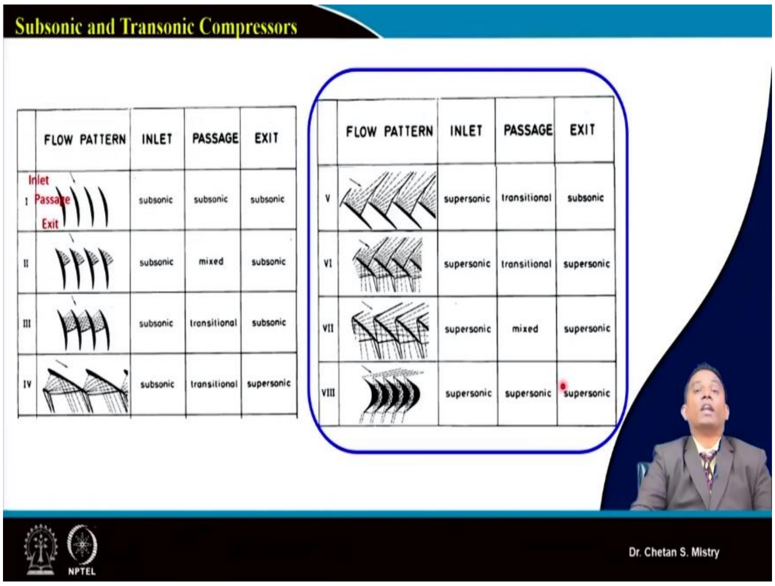

Let us see. So, here, if we look at, for subsonic as well as for say transonic compressors, we are having say different flow patterns. So, we can say here, this is what we are defining as an inlet. This is what we are defining as a passage between two blades or two airfoils and this is what is my exit. So, we can have our inlet to be subsonic. So, these all, that’s what is subjected to subsonic flow; within the passage here, you can say my flow is going subsonic and my exit flow is also subsonic, okay. So, we can say this low speed compressor or say research compressor are of this configuration.

We will be having say inlet flow to be subsonic. My passage flow will be going mix, that means we will be having subsonic and supersonic flow within the flow passage. And, the exit will be subsonic. We also will be having say configuration in which we will be having transition of the flow, that’s what is happening within the blade passage. And, this is what is of special kind of airfoils where my entry will be subsonic, my flow passage where my flow will be transitional and my exit will be supersonic, okay.

Now, this is what all we are discussing in sense of subsonic entry condition. What is our interest is my entry condition is supersonic. So, here you can see, my entry here is supersonic within the passage, I will be having transitional flow that means from supersonic to subsonic and my exit will be subsonic, okay. Now, here for say next configuration, my entry configuration is supersonic, my flow passage where I will be having my flow to be transitional flow and my exit flow will be supersonic flow, okay.

Same way here in this case, for this kind of airfoils, we are having entry flow to be supersonic, mix kind of configuration within the passage and my exit will be going supersonic. Now, this is what we can say if impulse kind of configuration, where we will be having entry Mach number or entry flow to be supersonic, my passage flow also will be supersonic and my exit flow will be supersonic.

So, you can say, when we are looking for our entry Mach number to be supersonic, we are looking for some special kind of airfoils. These airfoils which are different from what all we have discussed for subsonic configuration, okay. So, this is what is a region, that's what is of our interest at this moment.

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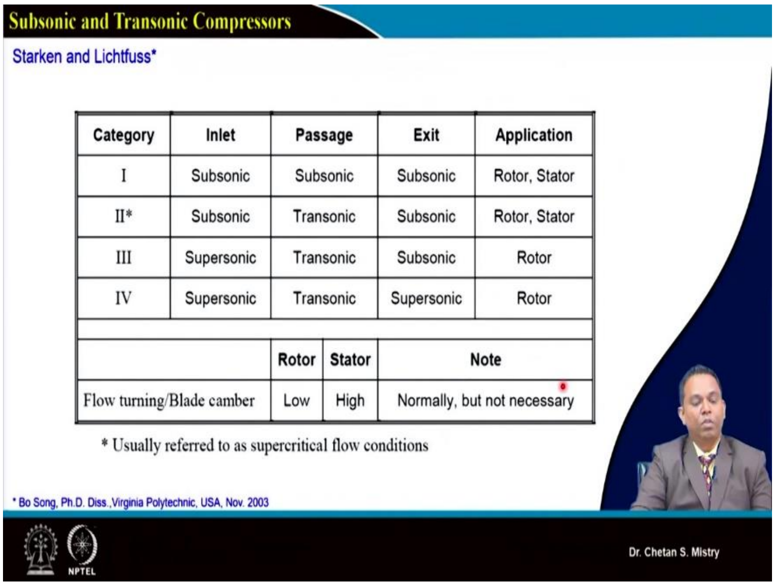

Category	Inlet	Passage	Exit	Application
I	Subsonic	Subsonic	Subsonic	Rotor, Stator
II*	Subsonic	Transonic	Subsonic	Rotor, Stator
III	Supersonic	Transonic	Subsonic	Rotor
IV	Supersonic	Transonic	Supersonic	Rotor

	Rotor	Stator	Note
Flow turning/Blade camber	Low	High	Normally, but not necessary

Now, categorically people they have defined as say category 1, 2, 3 and 4 where we are having entry condition to be subsonic or the supersonic. So, we can say, this is what is of category 1 mainly for rotor 1 and rotor as well as for stator, we can go with say subsonic kind of configuration.

Now, category 2, that's what is of say supercritical flow conditions where we will be having entry condition to be subsonic, my passage will be transonic and my exit will be say subsonic, that's what is more common for rotor as well as for the stator. The category 3, people, they have defined as say supersonic entry condition, transonic…say…passage condition and subsonic flow condition at the exit mainly for rotor, people, they are preferring. So, we have discussed all about these configurations. We will be having say supersonic entry condition, transonic passage condition and exit condition to be supersonic, this kind of configuration we are looking for in rotors, okay.

So, these are the four categories what people they have explored over the years, okay. So, this is what is the compilation of data, that's what we have received from one of the PhD thesis by Song and he has categorized that as say 1, 2, 3, 4, okay. And this is what is of our interest.

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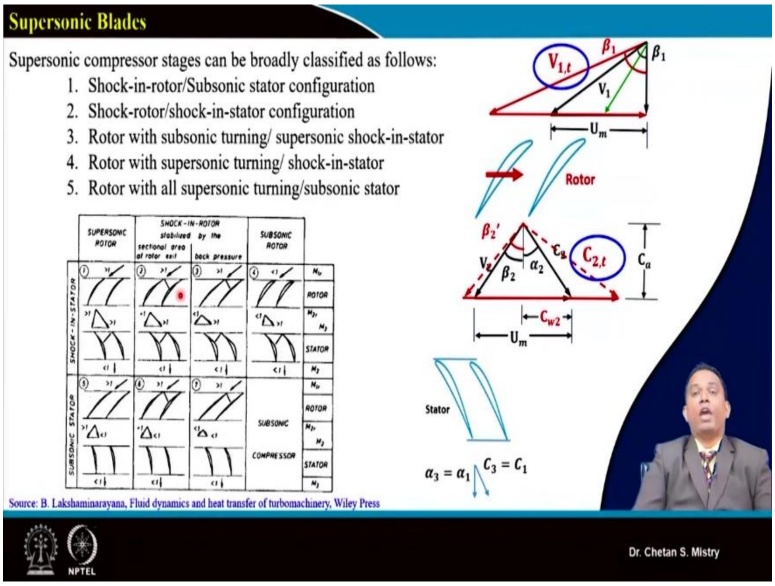

Now, say supersonic compressors, that's what can be categorized in a different way, okay. It says, we will be having say shock in a rotor or we can say subsonic stator configuration. So, we will be having shock, that's what is subjected for say rotor and my flow within the stator will be subsonic. Second category, it says shock in rotor and shock in stator configuration. Third, it says rotor with the subsonic turning and supersonic shock in the stator. Next category, it says rotor with the supersonic turning and shock in stator, rotor with all supersonic turning and subsonic stator.

So, all this kind of configuration what people they explored. Here in this case, this is what can be clearly understood. So, just try to understand what is happening at the entry of my rotor, what is happening at the entry of my stator, what is happening within the flow passage and what is happening at the exit, that's what is help us for categorizing the supersonic compressor. Do not get confused in sense of transonic compressor and supersonic compressors.

So, during 40s to 60s, 70s, people, they have designed supersonic compressors, which were giving very high pressure rise that may be in the range of say maybe 1.8 to 2.2 - 2.3. But the problem they were facing with those compressors are say reduction in the efficiency because that's what is subjected to very high losses. And as the reason why the interest for the development of supersonic compressor, that's what was say denied or that's what was reduced during that time. Again, as per the expectation, people, they are moving towards the development of say supersonic compressor or say transonic compressors for the next future Aero Engines.

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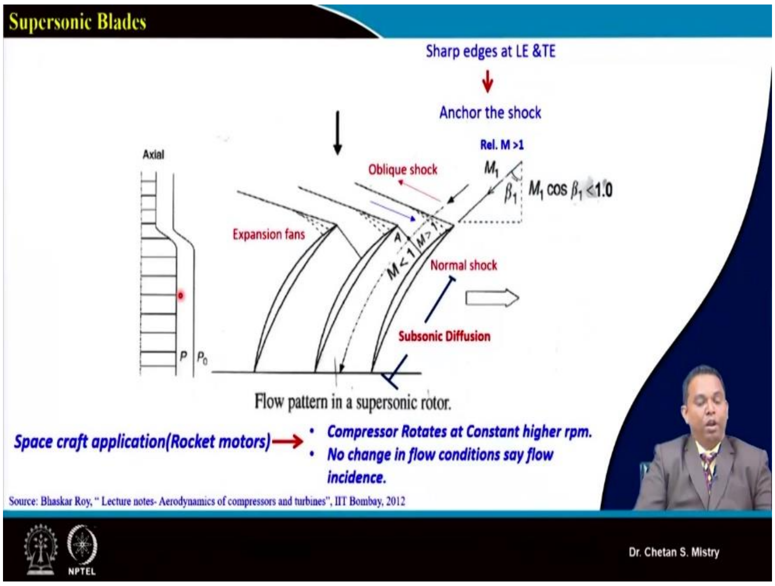

Now, let us try to understand what exactly is happening here. So, we can say, this is what is the airfoil which is having sharp leading edge, when my flow, that's what is entering at say supersonic conditions, say may be in the range of 1.2-1.4. And because I am having my sharp leading edge, the shock that will be attached at the leading edge, we can say this is what is at say anchored at the leading edge.

Now, because we are having the curvature of the suction surface in such a way that the flow, that's what will be subjected to formation of say this as expansion fans, okay. So, this is what is representing the expansion fans. So, upstream of my shock, this shock we can say, as oblique shock; this oblique shock, that's what will be having say downside based on the curvature of my suction surface, this angle, that's what will be defining the formation of the expansion fans. So, this is what is one of the leg, that's what is moving away from the blade.

Now, second leg of that oblique shock, that's what will be moving towards say the suction surface of my blade. And here, this is what we can say, it is acting like a passage shock, sometimes people they used to define that as a normal shock. It is kind of normal shock, that's what is happening here. And what we know upstream of my normal shock, my flow will be supersonic and downstream of my normal shock, the flow will be subsonic. And here in this case, we can say now the whole flow, that's what is happening within the blade passage; this passage, that is nothing but the subsonic flow, okay. And this passage shape, that's what is like a diffuser, we can say, we will be having subsonic diffusion, that's what is happening here, okay.

Now, here, if you try to understand what exactly is happening, we can say this is what is representing the axial flow direction. So, because of presence of our normal shock, we will be having sudden rise of static pressure as well as my total pressure.

Now, here, this is what we are looking for. We know by designing my subsonic airfoils, we are able to achieve the pressure rise, that's what is limited. Now, here in this case, what is happening because of presence of my normal shock, I will be having sudden rise of pressure, that sudden rise of pressure, that's what will be giving me expected pressure rise from these blades. And that is where we need to think of opting supersonic kind of compressor or supersonic kind of flow by taking the benefit of normal shock, we are able to achieve high pressure rise.

So, take this benefit. So, aerodynamicist, those who are working for say development of different airfoils they realize this part and later on they say like we will be taking the benefit of this supersonic flow.

Now here in this case, this edge is sharp edge and that is the reason why my flow, that's what is getting anchored or by shock, that's what is getting anchored. This kind of configuration, that's what has been most widely been used for spacecraft application or rocket application, where my operational time that's what is very low and my compressor, that's what is rotating at the constant speed, okay. And, when we say it is rotating at constant speed and operational timing is low, there are less chances for my flow incidence to change. And that is the reason why we are able to achieve very high pressure rise by using this kind of configuration, okay.

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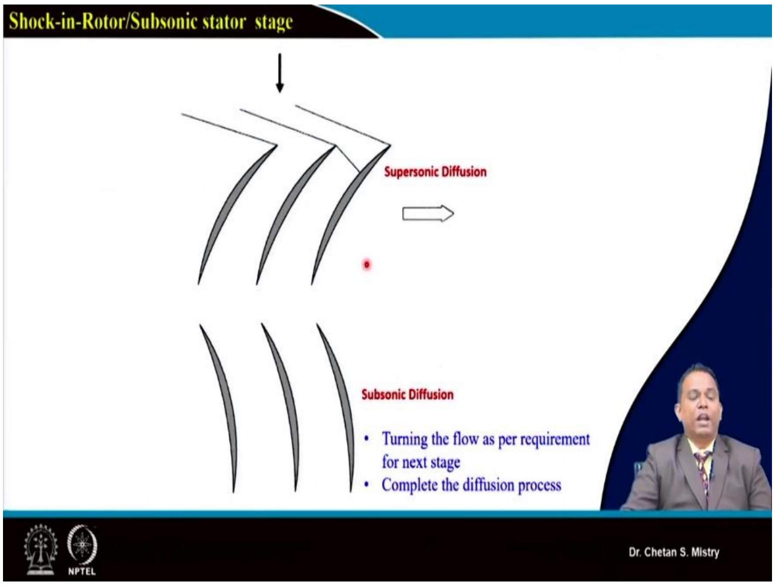

Now, let us try to understand what we say as shock in rotor and subsonic stator configuration. So, here in this case, we can see, we are having supersonic flow, that's what will be incident on my rotor. When it is incident on the rotor, we will be having the formation of oblique shock near my leading edge, okay. And here, we will be having our passage shock or terminal shock or we can say normal shock, that's what will be acting like having diffusion to be happened.

So here, the diffusion, that's what we are getting, that's what is because of formation of this normal shock. Downside of our normal shock, we will be having our diffusion, that's what is happening subsonically.

Now, the main requirement for the stator, that's what is say for the turning of the flow; and, you know, more complete diffusion, that's what you will be getting by having subsonic say stator. So here, my flow is subsonic. Here, I will be having my flow to be subsonic. So, this is what is shock in rotor and subsonic stator; this is what is most widely been accepted kind of configuration as we have discussed earlier.

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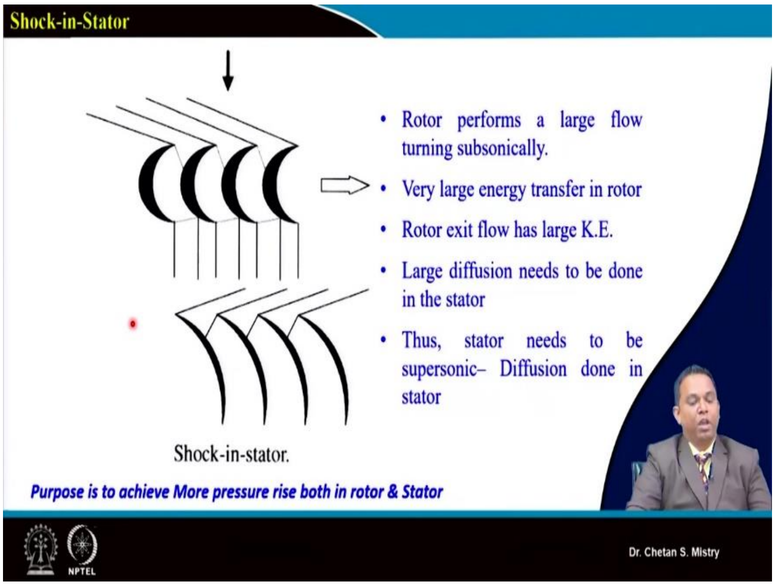

Now, there are other configuration in which we will be having shock in stator. So, you can see, here, this is what is a kind of airfoils for the rotor. So, whole lot of acceleration, that's what is happening or the large turning of the flow, that's what is happening inside the rotor, okay. When the large turning, that's what is happening, the exit kinetic energy, that's what is coming to be larger. They can say, the flow, that's what will be coming out with larger absolute velocity. And, that's what will lead to have the flow at the entry of the stator to be supersonic, okay.

Now, here in this case, the whole diffusion, that's what is expected to be done by stator, okay. In order achieve high pressure rise, both for rotor and stator, this kind of configuration, that's what has been used, okay.

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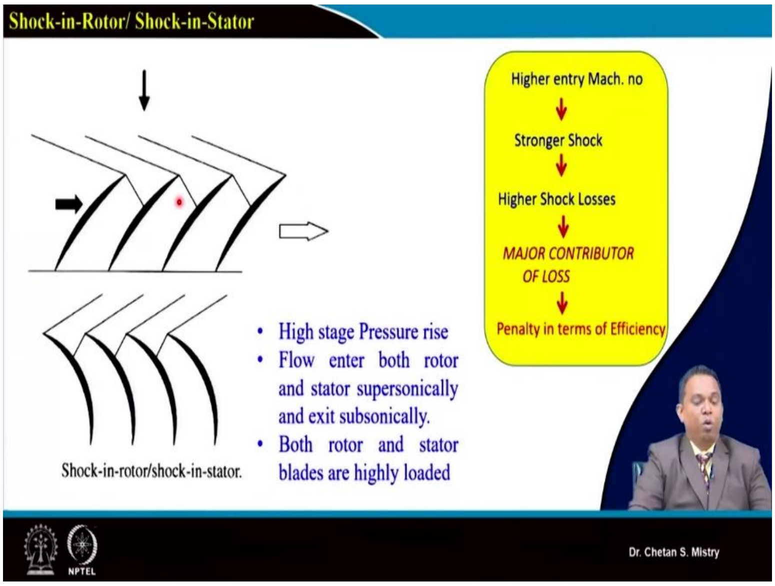

Now, let us see, this is what is representing shock in rotor and shock in stator configuration. So, in line to what we say when we are expecting our pressure rise to be large, we are expecting higher performance of our compressor, then this kind of configuration, that's what has been used. So here, we are having our shock, that's what will be standing at the entry of my rotor. Similarly, at the exit of rotor, we will be having higher absolute velocity and that's what will lead to give the supersonic flow at the entry of the stator, okay.

And, here this rotor and stator both are highly loaded. There is nothing wrong in having this kind of configuration. But what our aerodynamics says, if we will be having higher entry Mach number, my shock that will be stronger one; when we say, we are having stronger shock, the losses will be larger and that's what will lead to reduce the efficiency as a penalty. And that is the reason why this kind of configuration, that's what is having some special application, where the duration of the operation will be sought. There, people, they are preferred to go with this kind of configuration.

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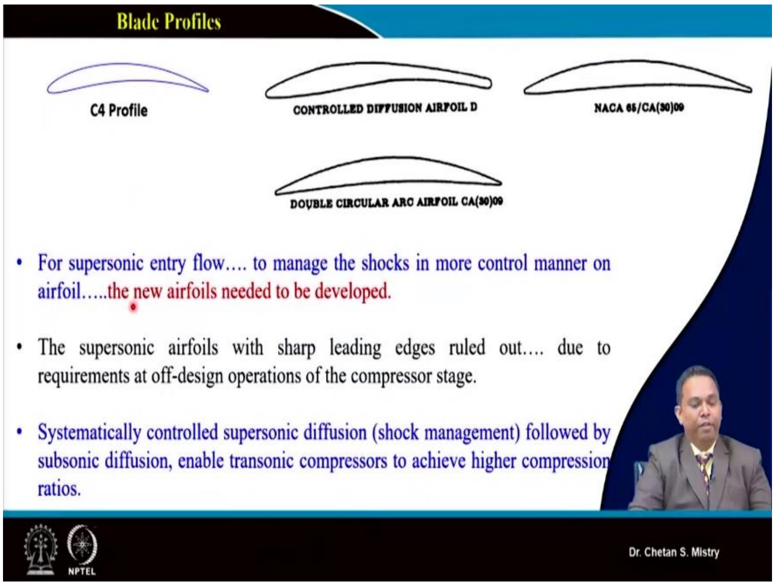

Now, what we realize from all this configuration what all we are discussing is, you know, like what blades or what airfoils what we are using. Suppose we are using say C4 kind of airfoil, that's what cannot be adopted or cannot be used for this kind of configuration or for this kind of compressor, okay. When we are having supersonic entry flow, we need to have more control on the shock formation. And, that's what is demanding for new kind of airfoils need to be developed, okay.

Secondly, if you are looking at my supersonic flow, the sharp leading edge, that's what is creating the trouble. The sharp leading edge what we are discussing, you know, that's what is helping us for anchoring the shock. But what happens when my flow or my compressor it is working under off design condition. Say, suppose it is operating under subsonic condition, this subsonic condition, sharp edge, that's what will be acting like, you know, the flow separating device.

So, we will be having flow separation, that's what will be happening at the leading edge. And we can say, my entire blade or entire airfoil, that's what will be going under stall condition. So, this sharp leading edge, that's what is need to be addressed. So, that's what is demanding for having curvature for this leading edge and trailing edge.

Now, how by flow, that's what is behaving on the blade passage, that's what is very important. So, control of say supersonic diffusion, that's what will be followed by the subsonic diffusion, that's what is required to be addressed. So, now we can say, what all airfoils we are having for the subsonic configuration, that's what will not be helpful for say supersonic flow configuration. And, that's what is demanding for the development of new kind of airfoils.

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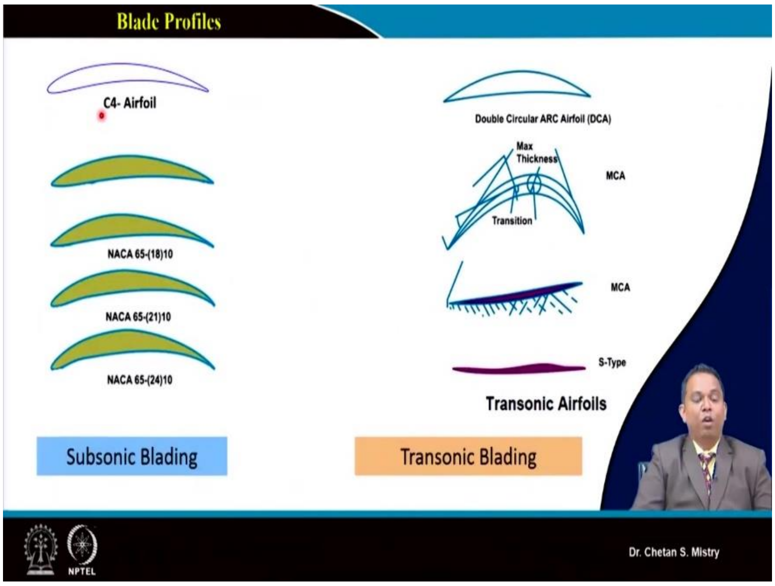

Now, let us have a look at, if you recall when we were discussing about the aerodynamics of say axial flow compressor in sense of airfoils. So, we have discussed about the C4 airfoil, we have discussed about NACA 65 airfoil; these airfoils are the subsonic airfoils. Now, the subsonic airfoils, that's what is having the limitations for application for the supersonic flow and in order to address this kind of configuration, we are moving towards the development of new airfoils and some of them, they are double circular arc airfoil.

So, here if you look at, I am having this as one circular arc, this is what is my second circular arc, okay. And, you know, here we are having say, if we enlarge in this particular region, we will be having slight curvature or slight rounding near the leading edge, and the same way, we will be having slight turning or rounding near the trailing edge.

Now, this flow passage, that's what we are making as a suction surface, that's what will need to help us in sense of managing the flow within the flow passage. So, the radius what we are selecting, that's what is very important for say our double circular arc airfoil. Here, for say double circular arc, say maximum thickness we can say, that's what is at the mid station or say 50% of my chord.

Sometimes, you need to play with this in sense of managing the flow within the flow passage. And, that is the reason why this comes to be rule out when we are moving towards say higher supersonic configuration or higher Mach number configuration. When we say, when we are moving towards the higher Mach number configuration, this is what is a next kind of airfoils, people, they have developed, that's what is called multiple circular arc airfoil. We can say, this is what is my one circular arc, second circular arc, third circular arc, fourth circular arc.

So, we will be having combination of different circular arcs, okay, that's what will be used to make the airfoil. And here in this case my maximum thickness, that's what is having the flexibility, I can move towards say my leading edge, the maximum thickness I can move towards my training age, okay. This is what is a flexibility with the multiple circular arc airfoil. Here, this is what is for the representation purpose. This multiple circular arc is not this much cambered. Be careful, okay!

So, we are having say double circular arc airfoil, we are having multiple circular arc airfoil; this multiple circular arc airfoil, that can be arranged in a different configuration also. So, here if you look at, this is what is multiple circular arc airfoil, that's what has been arranged in a different way, okay. Now, this is what is with the special requirement.

Day by day, the inlet Mach number or entry Mach number, that's what is going to increase. So, these days, people, they are talking about entry Mach number in the range of 1.6-1.8. So, this is what is a special kind of airfoil, that's what has been developed, which is defined or named as say S kind of airfoil or S type airfoil. So, these all are the airfoils which are being developed in order to meet the requirements, okay.

So, in next session, we will be discussing about how these airfoils or how my flow or how my behavior of Mach number, that's what is changing within the blade passage, how our diffusion, that's what we are achieving in sense of supersonic diffusion and subsonic diffusion, that's what all we will be discussing in the next session.

Thank you very much for your kind attention. Now, it is advised that you just go with the fundamentals of gas dynamics in order to understand this concept clearly and cleverly. Thank you. Thank you very much!