Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture – 11
Stage Configuration and parameters (Contd.)

Hello, and welcome to lecture-11 for the course on Aerodynamic Design of Compressors and Fans. In last lecture we have discussed one of the tutorial that's what was based on different configuration, we say stage configurations. Now, with these fundamentals let us move ahead.

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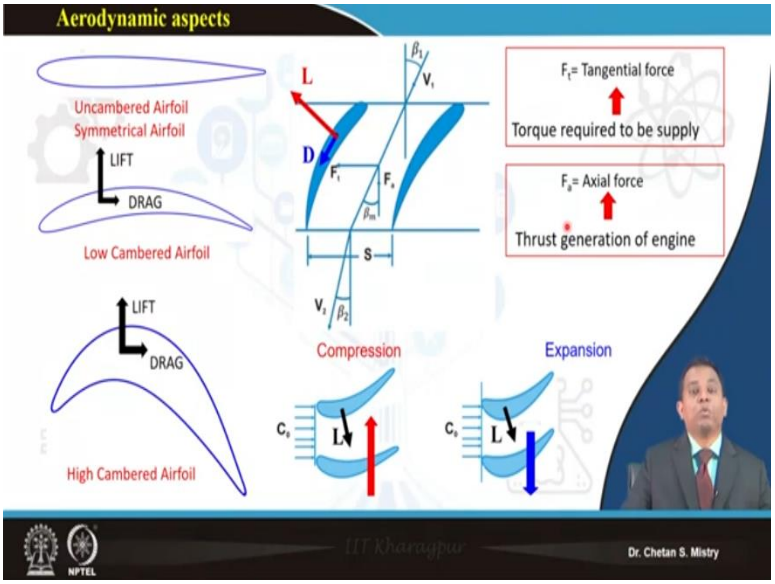

So, here, today we will be discussing about the aerodynamic aspects of our axial flow compressor. In order to understand, if you look at, we are having airfoil, this is an airfoil. We can say this airfoil as say uncambered airfoil or we can say as a symmetrical airfoil. So, we know airfoil it is defined as an aerodynamic body, okay, that's what will be giving a distribution of my pressure on upper and lower surface. If I am talking about the symmetrical airfoil, for that I will be having equal distribution of pressure that's what will not be generating any kind of lift. Now, in order to generate the lift, there are different means.

One of the mean is I will be giving my flow at certain angle here. That's what will be changing the distribution of my velocity on the airfoil. And that's what will be changing the distribution of pressure and will be giving me the lift. But, for our purpose for axial flow compressors and fan, these airfoils they are being used for different purpose. We have seen in last few lectures, say we are having different flow angles, that's what we say blade angle or blade air angle. That's what is giving me by β_1 and β_2 at the entry and exit that is what we say $\Delta\beta$.

Now, if I will be incorporating those angles, that's what will be giving me this kind of airfoil, okay. So, here if you look at my flow that will be entering at some angle β_1, and my flow will be leaving at some angle β_2 this is what is called cambered airfoil. So, for our compressor and fans, we are using cambered airfoil. This is what is having lower angle that is why our lower cambered angle that is why it is defined as a low cambered airfoil. Now, we know the property of airfoil that's what will be giving me my lifting force. So, we must realize we have discussed earlier also, I will be having more pressure here or say large pressure here compared to my say upper surface.

So, I, let me introduce that, that upper surface, that's what is known as a suction surface; this lower surface is defined as a pressure surface. So, on pressure surface, I will be having higher pressure; on my suction surface, I will be having lower pressure. This differential pressure we have realized that's what is because of how my flow that will be moving ahead, okay. And with say imaginary stream lines, we have discussed how my flow that's what is moving on my suction surface and my pressure surface. Now, perpendicular to that force, that's what is defined as a drag force. Our major interest that's what is on the lift force.

Now, let me introduce a new kind of airfoil here. So, here if you look at, this is what is having my angle – blade angle, that's what is very large, that's what is called say large cambered airfoil. These large cambered airfoils those we are using for turbines. Now, let us try to understand here, for this also, I will be having my lifting force, I will be having my drag force. So, these phenomena what we are discussing in sense of generation of lift that's what is common for wing. We can say for now cambered airfoil that's what we are using for axial flow compressor, my cambered airfoil for turbine they are also generating the left, okay.

Now, in order to understand this part, let me put this as a force. So, this is what we have discussed as a lifting force, and I will be having drag force. Now, here in this case for the compressor, we know my pressure at the entry that's what is lower, my pressure at the exit that's what is say higher. That means, if you remember, we are used to say in aerodynamics or even in fluid mechanics, we used to say when my entry pressure is lower, and my exit pressure is larger, that's what we are defining as an adverse pressure gradient. So, now using differential pressure, I will be using adverse pressure gradient, okay.

Now, in line to that, if we are talking about the turbine, where I will be having my entry pressure that's what is large and my exit pressure is lower. And that's what we say as an expansion process and we need to say this as a favorable pressure gradient because my flow that will be moving from high pressure side to low pressure side, okay. So, that is the reason why we are having two different airfoils. You maybe having questions, sir, what is the reason why we are having this kind of low cambered airfoil for compressor? Why we are having high cambered airfoil for turbine?

We need to realize here, when we are working under adverse pressure gradient, mainly because of adverse pressure gradient, I will be having more chances of my flow to get separated. My flow will be getting separated mainly from the suction surface, okay. So, majority of work or majority of research that's what is going on. What is happening on the suction surface of your compressor blade and what is happening on your suction surface of the turbine blade?

Now, here if you look at, these are the two airfoils I have arranged in such a way that this is what is representing my flow passage. And as we have discussed earlier, here we are having this inlet area and this is what is my outlet area. If I say my entry area is lower, my outlet area is larger; we can say this passage as a diffusing passage, okay. Now, if this is what is your case, you just look at this is what is a second arrangement. Here in this case, if you look at carefully, here I am having my entry area, this is what is my exit area and if you look at carefully, my entry area is larger and my exit area is smaller.

That means it is making say converging passage or nozzle kind of configuration. So, now onwards as and when you will be looking at the blades you must realize, is it a compressor blade or a turbine blade? What are the two ways? You just look at what is happening between the passage and just look at the cambered of that airfoil or camber of that particular blade, okay. So, as we have discussed we are having our lifting force that's what is acting in this direction. We can say from pressure side on and the substance side, if you realize this is what is representing my lifting force; my flow that will be entering in the passage from this direction.

Now, in compressor we want to compress our working fluid. So, we want to do work on our working fluid. In order to do that part, we want to utilize our lifting force. This is what we have discussed earlier also. So, basically the purpose of using this airfoil it is to utilize the benefit of your lifting force. So, what it will be doing? We want to use this as our say… benefit for our application. Then, I need to have say my rotation of wheel that need to be from my suction side to the pressure side. So, if you look at carefully, my flow will be entering from this side when it is passing to that, we are taking the benefit of this lifting force.

And that's what will be helpful for us in order to compress my working fluid. Now, in line to that, we are having turbine blade in that also we are having lifting force. Now, you know, when my flow that's what will be passing through this passage, I want to extract the work from my working fluid because we are using this for our expansion process, or we want to extract the work from our turbine blades. So, what we need to do? In order to take the benefit of this lift force, we need to rotate our wheel from pressure side to the suction side, okay. So, be careful about how your rotation that's what is happening.

Many times, looking to this blade, people they are getting confused with there is nothing to confuse. Here, like we need to realize what we are doing; we are taking the benefit our lifting force. We are taking the benefit of our force in order to compress the working fluid, in order to get the expansion work. So, this is what I say as a compression work and this is what I say as an expansion work, okay. Now, here in this case, if you look at we have discussed in last session for say momentum; so, we are having two forces.

One, that's what is axial momentum and second, that's what is tangential momentum. So, basically, we have discussed my tangential momentum, that's what is helping us in order to have your torque to be supplied to your blades or your rotor, okay. So, basically your compression work, that's what we are getting because of this tangential force, okay. Same way, if I am talking about say… second force, that's what is axial force; this axial force, that's what is useful to us in sense of generation of the thrust. Now, let me tell you, those who are from aerospace background and when they are referring the book and literature, and when they are learning, they are having understanding that thrust that's what has been generated by the nozzle.

That is what we are writing as $\dot{m}(V_{exit} - V_{\infty}) + Pressure\ Drag$, but that's what is confusing. You need to realize for gas turbine engine, all the components that's what is generating the thrust. So, we are having thrust generation by my rotors, and my stators, okay, for compressor. Same way, thrust will be generated by your combustion chamber, thrust will be generated by my turbine, thrust will be generated by say connecting duct. Thrust will be generated by say your nozzle and that is how we are getting overall thrust, okay. So, maybe if possible just go through the literature and read again.

So, here I want to say what is the benefit of using of our tangential force and axial force, okay. So, this is what is now giving us idea, like for compressor we are having our blade that's what is low cambered blade, or say it is low cambered airfoil. So, what I am naming here as camber, we will be discussing very soon, what is that, okay?

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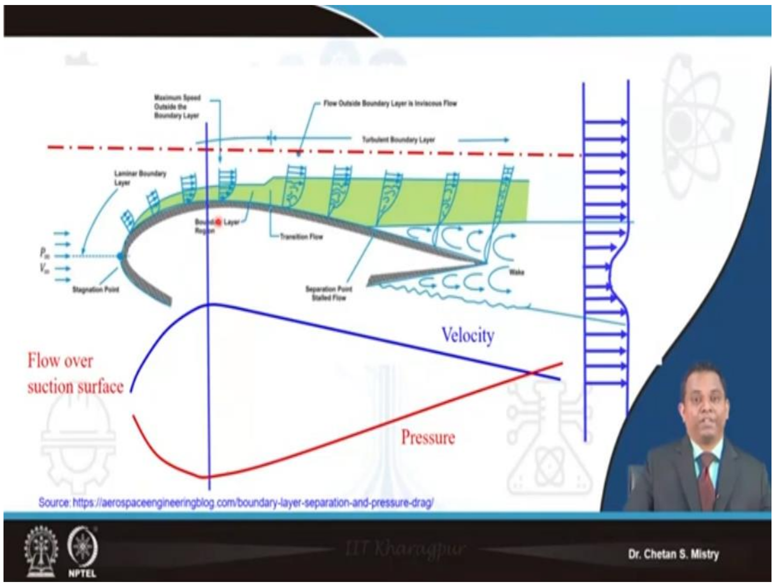

Now, let us try to understand what exactly is happening on my blade or on my airfoil. So, this is what is one of the good figure that's what is available online, you can see here. For this, say this is what is say my suction surface on downside I am having my pressure surface. Now, flow that's what will be incident here. So, this point that's what we say as a stagnation point, okay. Now, from our understanding, what we learn? Suppose, if I consider at infinite height, I will be having say you know streamline that's what is say parallel streamline.

And, here if you look at, when I am moving towards my 'leading edge', this region that's what is called leading edge, and this region that's what is called 'trailing edge'. And distance between this leading edge and trailing edge that's what is called 'chord', okay. So, what is happening near the leading edge? Because my area that's what is getting decreased, I will be having my acceleration of flow that's what is happening on my suction surface of the blade.

Similar situation that's what is happening even on my pressure surface. But, as I told our major concern that's what is happening on my suction surface. So, what will happen? Initially up to some distance, I will be having laminar flow on my suction surface. And here if you look at, since this is what is a solid body, I will be having the growth of my boundary layer all the way from my leading edge towards the downside, okay.

Here, somewhere if you look at, we are having thickness of this airfoil that's what is maximum. So, this is what is a region where I will be having maximum velocity. So, let me put velocity on my suction surface. So, here if you look at, say we are having our velocity that's what is flowing, or say velocity with which my fluid is flowing on my suction surface, that's what is saying me it is an acceleration of flow. On later part what is happening? Now, you can see this particular passage, that's what is shape like a diverging passage, okay.

Or you can say it is a diffusing passage, and that's what is happening, I will be having my deceleration of flow from say maximum thickness towards the trailing edge. So, somewhere here, I will be having lower velocity. Now, you know, when we are having acceleration and later on since we say I will be having this flow passage as a diverging passage my flow structure that's what is changing.

So, initially, I will be having my flow to be laminar flow, later on it will go in a transition mode, and downside if you look at, my flow is say turbulent flow. So, mainly when we are discussing what is happening on my blade surface, we used to say we will be having, up to certain length, laminar flow. After that we will be having short length for transition and immediately that will be going for the turbulent region.

When I say it is going on the turbulent region and when we are having this as an adverse pressure gradient because of diffusing passage. So, at some distance on my suction surface, I will be having the flow separation that's what will be happening. So, somewhere here, that's what is called say stall point or we can say this is what is say inflection point, from where I will be having my flow separation that's what is happening.

Now, what is happening? Because of that, you know, my flow that is supposed to be follow my trailing edge also, it will not be following my trailing edge. So, flow that will be coming out with a different structure, that's what is defined as a wake structure, okay. Now, let us see what is happening on my pressure. So, you know, initially when I am having my acceleration of flow, that's what is happening in the initial length up to maximum thickness, where I will be having say decrease of pressure. And if you recall, when I was discussing about the construction of axial flow compressor, that time we were discussing my flow that will get sucked from this leading edge.

And that is how the flow continuation that's what is happening in our axial flow compressor. Later on we can say, since my velocity it is decreasing and this passage that's what we say, we can assume that to be diffusing passage, I will be having the rise of pressure, okay. Now, this is what is very interesting and very important case, okay. Now, on downside if you look at, suppose say, I will be using my pitot static tube, and if I will be measuring my velocity in the downside, you will see this is what is my nearly uniform flow on both the side. But, within this region I will be having the deficiency of my velocity.

And this is what is known as a generation of my wake, okay. Now, when we are discussing about the airfoil, you will get shocked, you will say like what is the use of all these phenomena? We will be discussing very soon what is the use of, what flow that's what is happening. And let me tell you well in advance, we are preferring to have our flow to be more turbulent on suction surface, okay.

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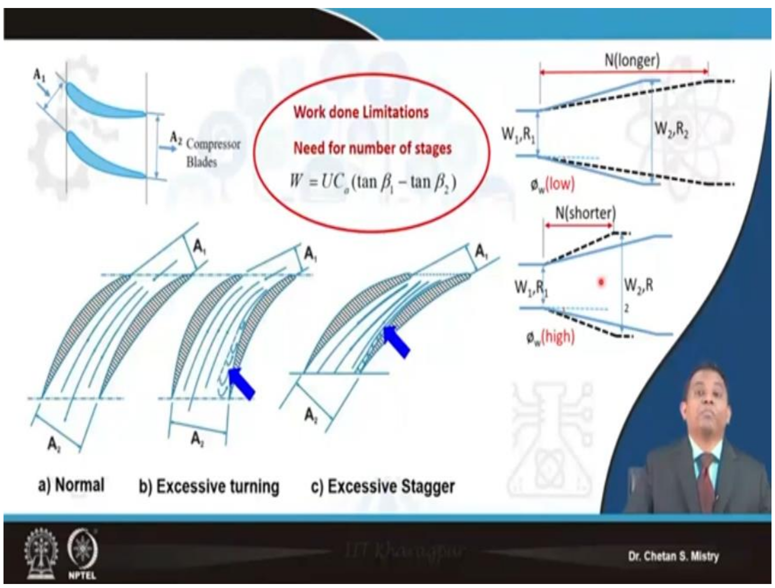

Now, let me move to the next slide. Say, this is what is discussing about say my work limitation, what is my work limitation? We say in order to achieve high pressure ratio or in order to achieve high work done, you are looking for my $\Delta\beta$ angle that's what is one of the parameter. Suppose, if you consider this is say my normal condition. So, normal condition in the sense I am having my area A_1 at the entry, my area A_2 at the exit, that's what is giving me diffusing passage. This is what is working absolutely fine. You can say this is what is un-stalled condition, where my flow is following both the walls.

Now, going aggressively, and you say please change the angle, blade angle. So, this is what is say… I am giving excessive turning to my airfoils or my blade. What will happen because of this excessive angle? I will be having my flow separation that’s what will be happening on my suction surface. So, you can say this is what is putting limit to us. And that is the reason as I told compressor that’s what is working under adverse pressure gradient. And if you will go aggressive in sense of loading or in sense of achieving high work done, you may need to pay in sense of flow separation.

When I say flow separation, the terminology we are using in compressor, it is called stalling of my compressor. And, you know, if it will be going for stall for some time, it will immediately go under surge condition and there may be chances your engine will get failed, okay. So, that is the reason why I say this is what is a heart of the engine, compressor always is the heart of engine. If it is not working fine, your engine is of no use. So, that is the reason why a whole lot of efforts people they are putting in sense of designing axial flow compressor in more systematic way, in a more aggressive way with detail understanding.

You will say, let us try to put, you know, this, tilt this blade or stagger this blade in this way. By doing this, you can say we are able to increase the length of my stage, okay. So, this is also one of the ways. But, when I will be going with this, this is also giving me the separation of my flow that’s what is happening on my suction surface. So, as I was saying, we are always correlating our fundamentals with the fundamentals of diffuser.

So, here if you look at, this is what is giving me what I am talking in sense of, you know, when I am changing my blade turning angle. So, this is what we have discussed if my length that’s what is shorter, okay; my diffusing length when it is getting shorter, I will be having separation problem. When I will be going with a longer length, I may not be having the problem with the flow separation. But, that’s what will be giving you or it is asking for the more space, okay. So, this is what is all fundamentals that’s what we need to learn and we need to understand, okay.

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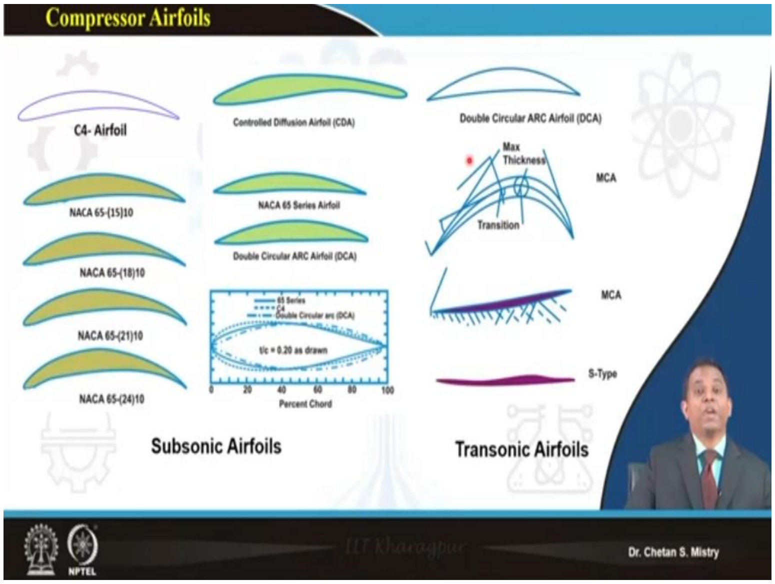

Now, let us move towards say, now airfoil we have introduced. Now, these are the list of airfoils, what people they are using these days for compressors and fans. So, here if you look at, this is what is say C4 airfoil, that is what people used to say it is a British airfoil. This airfoil, say NACA 65, say this is what is a family that's what was proposed by Americans, okay. So, these are NACA airfoils, NACA 65. And here if you look at, we are having NACA 65 airfoil, this is a second kind of airfoil in which we are having say double circular arc. So, here if you look at, I am having one circular arc here, I am having second circular arc here.

That is why it is called 'Double Circular Arc' (DCA) airfoil. Now, with the development of computational facility, computational techniques people they are able to design systematic blades or say airfoils. So, this is one of its kind, that's what is called 'Controlled Diffusion Airfoil' (CDA) where they are managing the flow systematic way, both on suction surface and pressure surface. And that's what is giving the benefit in sense of increasing the pressure ratio or pressure rise for particular design, okay. So, this all airfoils what we are saying? They are say subsonic airfoils, okay.

So, these airfoils when we are designing say low speed compressors, we are using these subsonic airfoils. Let me tell you, when we are talking about say HP compressor that is high pressure compressor in that high-pressure compressor, I will be showing you the blades in next session, where we are having the airfoils of this kind. Though we say this is what is rotating at the high speed, but still we are having those airfoils to be subsonic airfoils. Now, if you look at here on say our right-hand side, we are having double circular arc, that is what I told.

Now, in last session, we were discussing the limitation of higher rotational speed and higher axial velocity. And we say my flow that's what is going transonic and that's what is increasing the losses because of my shock formation, okay; and that is the reason it is reducing the efficiency. Now you can understand when you are going for more aggressive way of designing in order to meet your future requirements, you need to do your R&D. And that is how people they have come up with different kinds of airfoils. So, if you look at all these airfoils, they airfoils are transonic airfoils, okay.

So, here if you look at, all these airfoils, they are having their leading edge and trailing edge, they are sharp. The purpose here, it is to attach the flow or it is to attach the shock, okay. When we are having our sharp leading edge, I will be having my shock that will be attached with the surface of my blade, okay. Same way, for trailing edge also. And, here if you look at, for subsonic airfoils, where we may be having circular leading edge, it may be having elliptical leading edge, okay. Their purpose that's what is different, where you are looking for different kinds of application.

If I will be using say subsonic airfoil for say supersonic or transonic flow, you know, you will be having formation of bow shock. That's what is undesirable, that's what is not required. Because, my flow physics downside of my bow shock, that's what is not favoring; the reason for what we are using these airfoils, okay. So, here if you look at, this is what is say 'Multiple Circular Arc' (MCA) airfoil. You can say this is what is my one circular arc on suction side, this is my second circular arc, I am having say third circular arc and this is what is my fourth circular arc.

So, this kind of airfoils also people they have designed, okay. Not only design, say people they are doing initial design, then after, they are doing their testing in cascade tunnels and then after with the database what is available to them, they will be using that for application for design of say rotor as well as stators, okay. We will be discussing all these in detail as and when this session that's what will be coming. We have one special session that will be talking only in sense of transonic compressors, okay.

Here if you look at, this is a systematic way of using multiple circular arc, this is what is say S-shape kind of airfoil. So, earlier people they were talking, say for high bypass ratio engine, for low bypass ratio engine, we know my flow will be going transonic near the tip region, where they used to use these transonic airfoils. Now, with the maturity of technology, with use of your computational tool, with more detailed understanding of flow physics and good experimental results, people they are able to design the blades of the fan.

They maybe, you know, having say flow that's what is transonic and in that transonic region, they are using this kind of airfoils. The pressure ratio as on today in multinational companies, engine making companies, they are claiming that what has reached to around 1.8 to 2. So, you can understand day by day people they are going very aggressive in sense of doing the design of these compressors, okay. So, this is what is called say your transonic airfoil, okay. So, we are having subsonic airfoils, we are having transonic airfoils.

So, initially when you will be doing your design, you will be taking one of the standard data that's what is available to you, okay, in open literature, okay. Then after, as per your requirement, you need to modify the shape of this airfoils, okay, that's what is called custom tailored airfoil. That's what will be giving us the idea in sense of what we are looking for, that's what we are achieving, okay. Now, let me put the point here, say, in order to use, in order to design, in order to meet the competitive market, as I told the multinationals they are working a lot on design and development of this kind of airfoils, okay.

So, if companies they are registering their patents, most of the patents if you look at every year, those are going to this airfoil development, okay. So, they are making new kind of airfoils and that's what they are using for design of their compressors, design of their fans. And if you recall, I was showing you two rotor blades for fan, in which I was discussing say near the hub region or say near the end region if you look at, for the hub region we are having our flow to be subsonic, where we are using this kind of airfoils.

And when I am talking about say my fan, that's what is having say larger diameter or my blade height is larger near the tip region above 80 percent, 85 percent if you go your flow will go transonic.

And in that region, we are using this kind of airfoils. So, you can understand it is not always that your airfoil is uniform at hub, at midsection, and at the tip region. It maybe possible that you will be having different kinds of airfoils at different - different locations. That's what is putting more challenging part in sense of design, in sense of understanding, in sense of fabrication. So, you will be making rotor that’s what is having different kinds of airfoils.

Then you will be going for fabrication part, it may be possible that it will be more challenging to fabricate those kinds of blades and again you need to recreate your design, okay. So, mostly for high bypass ratio fan, you are having your subsonic airfoils near the hub region, you will be having your transonic airfoil near the tip region or shroud region. And for say high speed LP compressors, throughout the span, they may be going transonic, okay. And when we are talking about high pressure spool or high-pressure compressor, most of the stages, they are going subsonic, okay. So, here we are stopping with. We have discussed today about what all are the benefits of our lift force, that’s what is to use the airfoil section.

Then, we have discussed what is happening on our suction surface of the airfoil. And how this suction surface that’s what will be helping us in sense of achieving what we are looking for. Then, we have discussed about different kinds of airfoils, what we are using for the axial flow compressor and axial flow fans. So, here we are stopping with. Thank you very much for your attention.