Aerodynamic Design of Axial Flow Compressors and Fans
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Lecture 60
Design of Industrial Fan

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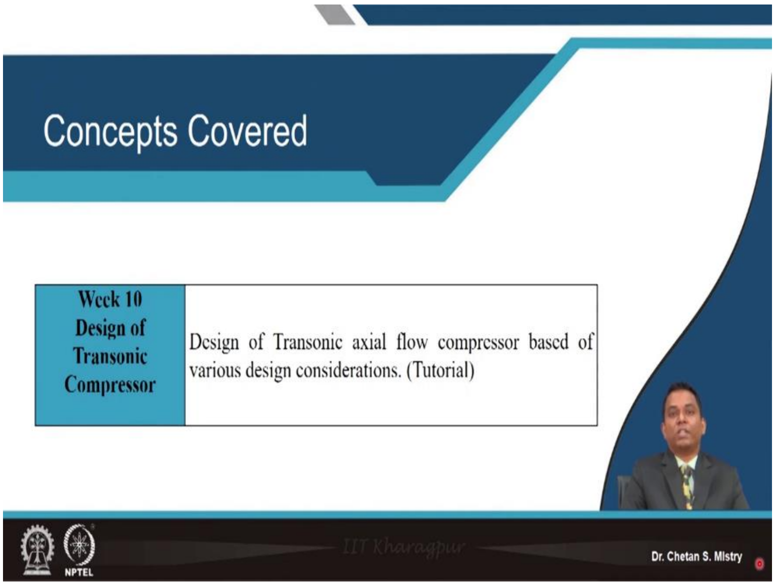

Hello, and welcome to week 11. This week is dedicated to design of industrial fan. And, welcome to the lecture 60. So, in last week we were discussing about the design of Transonic Compressor. So, in that Transonic Compressor, we have realized, we have discussed different design methodology that's what is including fundamental method. We have also discussed say design of fan using Controlled Vortex concept. We have discussed about different track configuration in sense of say constant tip diameter, constant hub diameter, constant mean diameter or we can say by assuming say various radius ratio.

We have also discussed about how exactly we will be configuring our design maybe which will be fulfilling the requirement of radial equilibrium, which may be violating radial equilibrium. So, now after doing all this the question may come in the mind say what is a recent trend for say design of such axial flow compressors.

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So, let us see, what are the recent trends for the design of high performance axial flow compressors. In overall if we look at, the design of high performance compressors, no doubt that’s what is required higher engineering excellence, higher engineering skills, detailed flow field understanding, detailed design procedures but after doing all these stuffs at some instant you will realize the design is a kind of art basically. So, what all designs what we have discussed let it be say subsonic compressor, let it be say transonic compressor, contra rotating fan, say the configuration as per our requirement all those stuffs, finally will come at the conclusion saying it is a kind of art, that's what we need to have. Because what kind of airfoils we are putting, what kind of dimensions we are selecting, what parameters we are configuring, all those things, that's what will be of artistic kind, okay.

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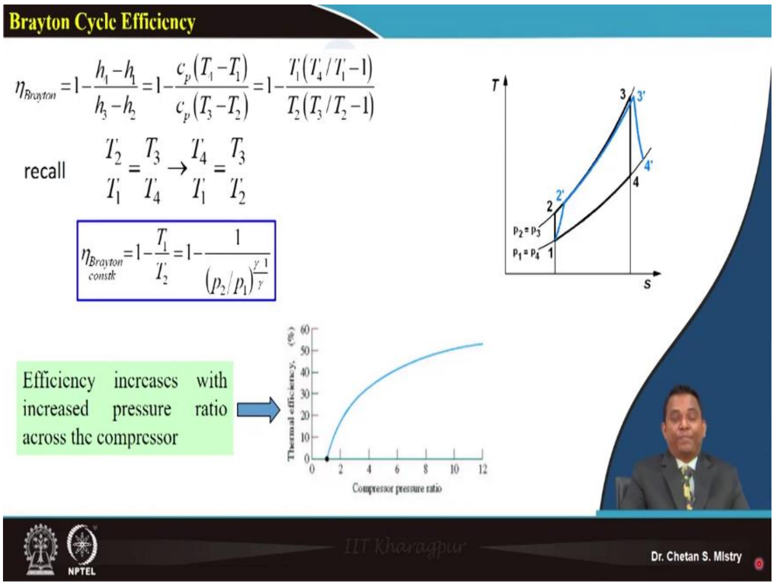

So, with this what all we know is from our fundamentals we know our gas turbine engine, that's what is working on a principle of say Brayton Cycle, let it be a land-based power plant or say aerospace application - aircraft power plant. So, purpose for both they are different but the logic in sense of efficiency what we say thermal efficiency because being engineer we are always having the thought to improve the efficiency, our target is to increase the efficiency.

We can say, for gas turbine power plant if we want to increase our thermal efficiency, it says you increase your pressure ratio. So, increase of pressure ratio, that's what is demanding for so many things, it says you can go with say separation ratio of 10. As on today, people, they are talking about say having say compression ratio…overall compression ratio of 64. So, this is what is required some kind of detailed understanding.

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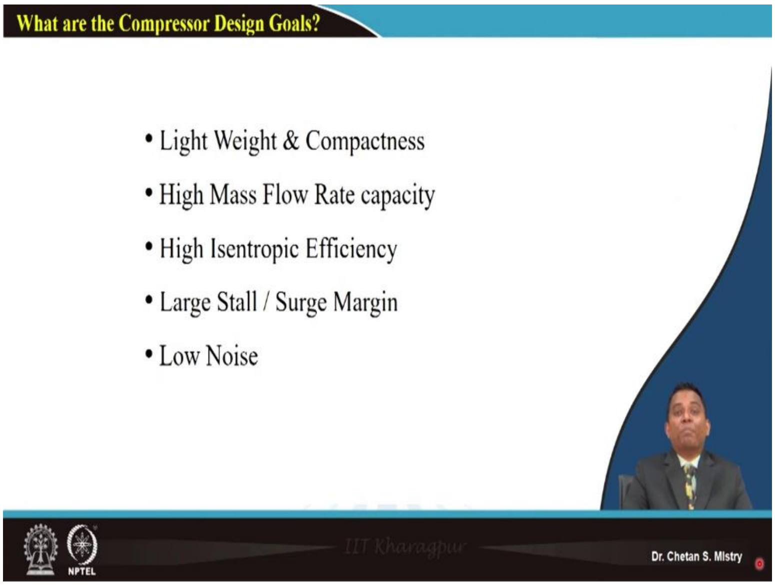

Now, when we are talking about the understanding then the things, that's what is coming in the mind is what is our expectation or what all we are looking for. When we are doing our design for the spatial application what all we are looking for, what are our expectations, or what are engine designer's expectations, or engine making companies expectation? They say, they will be looking for lightweight or the compact engines. When I say lightweight and compactness, that's what is having great impact when we are doing our design, we will see one by one.

Next, that's what it says it need to have high mass flow rate capacity because we know when we are talking about the application of this gas turbine engines for aircraft, we are looking for higher thrust. And, we know thrust is a product of mass flow rate into exhaust velocity. So, if we are able to increase our mass flow rate, we are able to increase our thrust. So, this is what is one of the thought process.

Next, that's what is coming is higher efficiency, as we know efficiency, that's what is a direct function in sense of our fuel consumption. And, day by day the price for the fuel that's what is raising and that's what is alarming for those aero engine companies. Because airliners, they are looking for efficient engines where they will be having lower specific fuel consumption. That means, you know, when we are targeting say lower specific fuel consumption the burden will come straight way on the designer. Next, that's what is say larger stall or surge margin. For aero application…aero engine application, this is what is very important; we are looking for broader operating range.

So, we have seen, when we are talking about subsonic compressor where we are having say kind of curve performance map, when we are talking about transonic compressor, that's what is having steeper operating characteristic. So, we need to have overall stage operating characteristic in such a way that it will be working under wider range and that's what will be giving the flexibility to the pilot.

Now, because of government regulation, say ACARE, as we have discussed earlier, they have put some constraints in sense of noise level, say mainly near the airport while taking off and lending, we are looking for the noise to be lower. And, this noise also is coming under the criteria for the designer. So, we can understand, say…when I say, we are doing our design for compressor stage or say multi-stage axial flow compressor, all these parameters that need to be bear in mind, okay.

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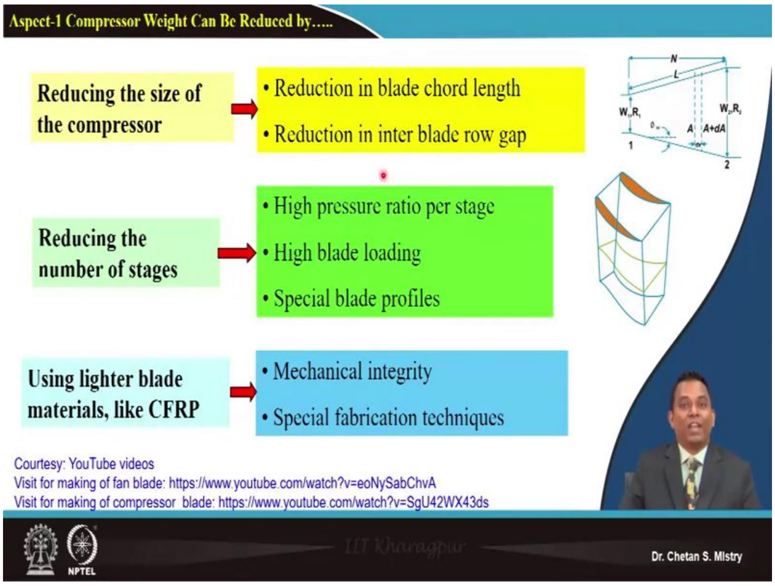

So, let us try to understand how people they are addressing these challenges. So, suppose if you are considering very first point, very first aspect; it says compressor weight need to be reduced or we can say we are looking for the compactness and light weight. What all are the possibility? It says you reduce the size of the compressor, reduce the number of stages, use lighter blades or special kind of materials for making of fans and compressor.

So, here if you look at, we are having different options available with us. Now, in order to address that what all alternatives in designs are possible. What it says? Reducing the size of the compressor; so, in order to reduce the size of the compressor, first possibility, what we have is to reduce the length of the chord, what we say, blade chord that need to be reduced. Second, that's what it says reduction in inter blade row gap, that means the gap between stator and rotor, the gap between two spools that need to be lower. If we are able to manage these things then we are able to reduce the size of the compressor.

So, we can say, this is what it says like by managing this parameters we are able to reduce the size or the length of the engine. Now, it says like you reduce your chord. So, what we realize, we have discussed in our fundamental lectures during week two, suppose if I consider my blade passage that is comprising of say diffusing shape, this is what is say my entry area, this is what will be my exit area, and we can say this is what is my length. And, if you recall, we have discussed my blade passage for the compressor or the fan, that's what is comprising of number of such diffusers.

So, we can say, at hub, mid station, near the tip region we are having different shapes of the blade or inter blade we are having diffusing passage. So, when we are opting with say going with decreasing the chord length, what will happen? This chord length, if I will be reducing, I will not be having sufficient amount of space for diffusion to happen on my suction surface. And, when I say, when we are not having that flexibility, then we need to go with the parameter that's what will be coming in the mind, that's what is say my diffusion factor.

So, diffusion factor, that's what is deciding what will be my pressure rising capacity of that particular station. So, under that condition what it says? If I will be reducing my chord, the alternative is to increase the number of blades, in order to achieve same diffusion. So, if that's what is your case, then what we are talking in sense of reducing the size of the compressor that may fulfill but at the same time it is contradicting in sense of increasing the weight of the engine because my number of blades will be increasing, okay.

Next, that's what is say reduction in say inter…gap between rotor and stator or may be gap between two spools. If we configure say the gap between rotor and stator, as we have discussed, that's what is nothing but it is defined in sense of percentage of chord. Suppose say, we will be arranging our rotor blade and stator blade nearby, that's what will lead to change the performance or that's what will lead to give say higher noise, that's what is one of the possibility.

Secondly, what will happen? Suppose, if you will be increasing the gap between rotor and stator, that's what will be increasing my length of the compressor at one instant; and secondly, what assumption we are making in sense of say absolute velocity coming out from my rotor that's what will be striking on the stator, those two absolute velocities are same. And, we are assuming those absolute flow angle also to be same; if you are putting this gap to be too large, that may not be valid and my stator may go under off design condition or maybe it will be reducing my operating range. So, this is what is one of the challenge.

Next, it says, reduce the number of stages. So, if we are looking for reduction in number of stages, what alternative we have is per stage pressure rise need to be increased, okay. So, suppose say we are having 10 stages, that's what is giving pressure ratio in the range of say 14. That's what we want to reduce to say maybe six or seven stages that means in order to achieve same compression ratio, we are reducing the number of stages and that is how per stage pressure rise that will be increasing.

So, when per stage pressure rise, that's what is increasing that means my blade loading will be increasing, okay. When we say our blade loading, that's what is increasing, that's what is demanding for special kind of airfoils that's what is demanding for special kind of bladings, this is what all we have discussed. So, we can understand here, when we say this is what we are looking for that is putting certain challenge in that sense, okay. Next alternative, that's what is say use lighter blade material, like you know, carbon fiber reinforced plastic kind of material, that's what we can use for making of fans.

Maybe for say rotor blades for compressor, we will be going with some lightweight material but at the same time the question will come with the meeting mechanical integrity, that's what is demanding for special kind of fabrication technology. And, that is where the whole research and development activities, those are going on. So, you can say, what all we are putting in sense of solution, in order to reduce the weight and in order to reduce the size of the engine, these are the alternative what people they have found. And, research at this moment, these days, that's what is going on to address these challenges, what we are looking on our right hand side, okay.

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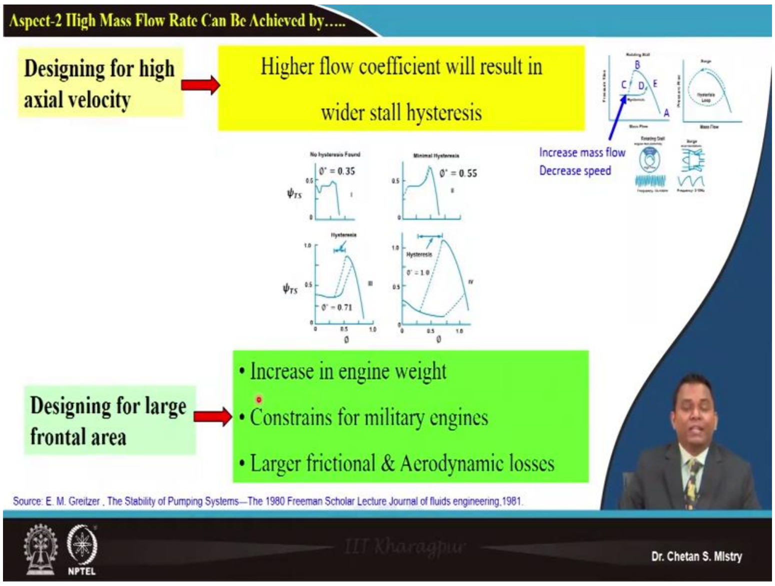

Now, next option what it says? You increase the mass flow rate. Suppose, if you are configuring say we want to increase our mass flow rate that means we have two options with us; one, that's what is to increase the axial velocity, and second option, that's what is say you increase the diameter, inlet diameter that means that's what is required larger frontal area. If we consider say higher axial velocity, that's what is creating trouble in sense of say wider stall hysteresis.

So, if you look at here, this is what is representing one of the performance map. For understanding, say this is what is my mass flow rate and this is what is representing my pressure rising capacity. If you consider here, say somewhere near say point A, somewhere point E, say that's what we can say is a say design point for us. Now, when I am decreasing the mass flow rate it says my pressure, that's what will be rising, that's what is the characteristic of compressor.

So, I will be having rise of pressure up to certain point, say point B; and, that point we are defining as say stall point. Beyond that if you will be reducing our mass flow rate, there is no further rise of pressure that's what is possible; and my whole compressor, that's what will be going under stall configuration. Based on what is the downstream component connected with the axial flow compressor, we can say that will go under surge condition. So, what will happen, when we are reducing our mass flow rate, in place of rising the pressure, my pressure will fall down, that's what is coming here.

Now, if you will continue running this compressor under that condition, there may be mechanical failure that will happen, that's what will be catastrophic failure. So, in order to avoid that kind of situation, what pilots they are doing? They are increasing the mass flow rate or maybe they are decreasing the rotational speed of the compressor. So, when we are doing that part; again, my compressor, that will be going from say point C to D to E, and again.

So, this is what is creating the hysteresis loop. So, you can see this is what is nothing but hysteresis loop. Now, what happens, say if we are considering different say higher axial velocity configuration that means my flow coefficient will be higher. So, this is what is one of the experimental reported work with different flow coefficients say 0.35, 0.55, 0.71 and if you look at, this is what is slightly on the higher side.

So, if you are having this flow coefficient in this range, we can say when we are having a flow coefficient that's what is lower, my pressure rising capacity is lower but I am not having any hysteresis kind of configuration. When we are moving with say flow coefficient slightly on the higher side, we will be having say minimum hysteresis. But at the same time when we are going with the flow coefficient in the range of 0.71, my hysteresis that's what is coming to be larger on the side. And, when we are going flow coefficient to be in the range of 1, we will be having very high hysteresis.

So, this is what is putting constraint in sense of having higher axial velocity. So, you can go through the paper, that's what is discussing about the stability of say pumping system. This is what is a scholar lecture, that's what will give more detail, more insight into this. Since, this is what is a design course, so, we will not be focusing more on these aspects but we can understand, this is what will be giving us idea, what we say in sense of wider stall hysteresis.

So, next option what we have is a large frontal area. So, when we are having larger frontal area what it will be doing? It will be increasing the weight of the engine, because my intake will be very large. If we are talking about application for say high bypass ratio engine, we are not having much difficulty, that's what we can install below our wing. But when we are talking about say military engine, for that military engine configuration, we are having constraint with the diameter because we will be fixing our engine in say fuselage.

Now, here in this case, this is what is a constraint with the military engine. Next, that's what will be having say higher aerodynamics and frictional losses. So, configuration of having say higher mass flow rate, that's what is little tricky in sense of handling our mass flow rate.

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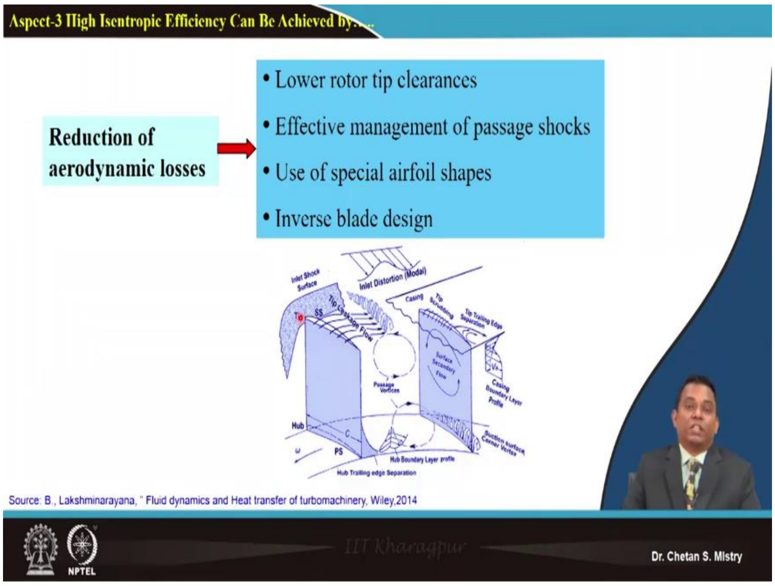

Let us move to the next option. It says higher isentropic efficiency of the compressor. So, what we know, my efficiency is directly related with the losses. We can say, if we are able to minimize the losses, we are able to improve the efficiency or increase the efficiency. Say, during 70s and 80s, people, they were talking about the efficiency in the range of 85%, 88%. Now, these days people, they are talking about efficiency in the range of 90%, 92%. And, as we have discussed, which stage we are configuring or which stage we are discussing, that's what will give the efficiency, what will be the range for those efficiencies.

So, if we configure, if you would like to reduce the losses what it says, lower the tip clearance. Suppose, if we configure lower tip clearance, it is but obvious that's what will be improving my performance and pressure rising capacity, that's what is reducing the losses. If you look at here, what we have realized, suppose if we consider, I will be having my flow…tip clearance flow, that's what is flowing from, say my pressure side to the suction side, and that's what will be forming the secondary flow passage along with the mainstream.

So, if you are able to minimize those losses, it is but obvious we are reducing or minimizing the losses, okay. Next, that's what is say effective management of my passage shock. So, when we were discussing about say transonic compressor, we have realized, if we will be able to manage our shock in a particular way, that's what will be helping in sense of rising my pressure capacity as well as the efficiency. If we are not managing our flow, then there may be chances that we will be having the flow separation that's what will be happening on the suction surface of my blade; or maybe under negative incidence configuration, we will be having the separation that's what will be happening on the pressure surface of the blade.

Next, it says we need to go with the special kind of airfoils, this also we have discussed. So, when we are talking about say subsonic compressor or subsonic fan, we are looking for special kind of airfoils. Same way, when we are talking about transonic compressors or transonic fans, we are looking for transonic airfoils. So, as per our requirement, we have modified the shape of our airfoils and the best way of managing the flow on the suction surface and the pressure surface of the airfoil, that's what will be managing the flow as per our requirement.

Now, here in this case, we can go with the inverse design configuration also. So, we will be having say our C_p distribution on pressure surface and suction surface, that's what is known to us. Based on that we will be configuring our say airfoil or we will be configuring our blade. And, that's what will be giving what design or what we are expecting. Here, this inverse design, I am not in that much favor because we can understand, we are doing our optimization for particular condition. When it is working under off design condition or say off design peripheral speed or off design axial velocity, that may not work as per our expectation, that may lead to reduce the operating range.

So here, this is what is one of the nice representation of loss model, that's what is saying like what is happening with our flow near the hub region. We can understand, this is what is representing say suction surface corner vortex, we will be having say growth of boundary layer because of presence of solid body; we will be having differential pressure between say suction surface and pressure surface, that's what will lead to make the passage loss or passage vortex, that's what will be forming. At the same time, we will be having secondary losses. Based on what is the kind of flow that's what is going inside my compressor, we can say, that's what is as an inlet distortion, accordingly my flow behavior that's what will be changing. It also depends on what will be my sock structure if I am talking about say supersonic compressor or transonic compressor, okay.

So, the next thing, that's what is to take care of these losses. So, this is also one of the research area, lot of universities and companies they are working together in order to address these issues. And, that is where I was talking, people, they are making new kind of airfoils, people they are making say innovative kind of blade design in order to minimize the losses and in order to improve the performance both in terms of pressure rise as well as efficiency.

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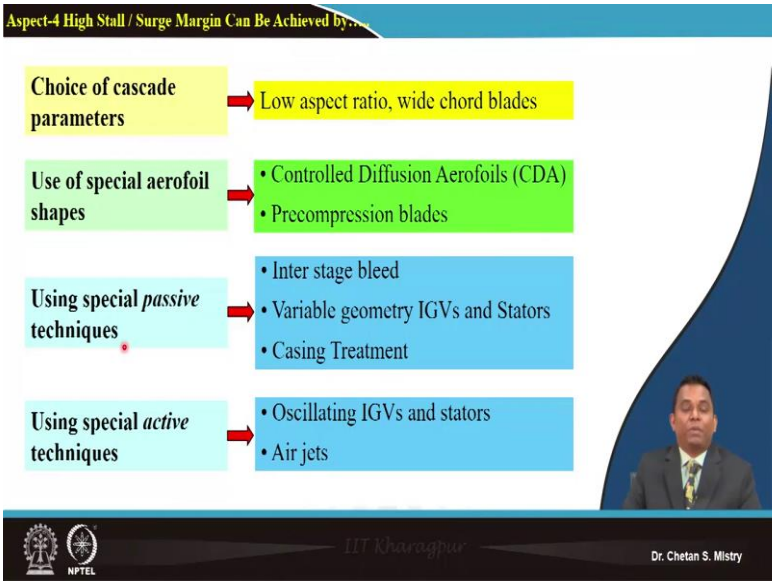

Now, if we configure, say next, that's what it say high stall or surge margin. Now, this is what is a special requirement we can say. Now, in order to achieve this margin to be large, that's what is always the designer and engine manufacturing company, they are looking for. What it says? Like, this is what can be handled by choice of cascade parameters, okay. Use of special kind of airfoil shapes, special kind of passive techniques, using special kind of active techniques. So, let us try to understand what we mean by this.

Now, as we have discussed during our design discussion, the approach is now towards the low aspect ratio blade and we are having wide chord configuration, okay. So, making of new kind of cascades or airfoil, that’s what is of interest at this moment. When we are having wider chord, we have realized we are able to manage our flow on suction surface, that’s what will be led to increase our operating range. Maybe, somewhere we need to compromise in sense of efficiency but that loss of efficiency and the gain of operating range, if this together if you are configuring, people, they are moving more towards wider operating range requirement.

Next, that’s what is say special kind of airfoils. What we have discussed is in sense of Control Diffusion Airfoils, that’s what is wide chord airfoil. We are discussing about the pre-compression blades, so just realize how nicely we are managing our shocks on the suction surface of the blade. So, these days people, they are talking about Multiple Circular Arc, they are talking about S shape of blades. Under that we are able to manage the compression on say blade surface. And, that’s what is helping in order to improve the operating range.

Now, people, they are talking about the passive flow control mechanism, say inter stage bleed. So, the air from say later stages that’s what will be taken out and that’s what will be injected near the hub region or maybe near the tip region according to the requirement; and that’s what is helping the operating range or that’s what is basically delaying the separation. Say, hub corners separation, that’s what can be handled by having this kind of blade. Even near the tip region also, people, they are exploring this kind of possibility. There are possibility to go with say variable geometry, that’s what is say variable inlet guide vanes or the stators.

So, most recent engine, that’s what is say upcoming engine, 6th generation aircraft where people they are talking about say variable inlet guide vanes, variable stator kind of configuration, that’s what is having special kind of application, okay. Under that configuration, this is what is coming into the picture. Now, casing treatment also is one of the hot area for the research; by having casing treatment, people, they are trying to broaden the operating range. Next, what we have is in sense of say active techniques. So, oscillating inlet guide vanes and stators, air jets. So, these are some of the research, that’s what is been going on in order to improve the stall margin. So, this is what is at the lab level at this moment, there is no straightway application to actual engine that’s what is existing.

So, far as active control mechanism, that’s what is coming. This active control mechanism, that’s what is required additional power source, additional actuating mechanism, that’s what is required additional component and that’s what is putting lot of constraint when we are talking about application in actual engine. While for the case of passive techniques, certain modification that's what will be helping. That is the reason why, people, they are preferring at this moment with going of say passive control mechanisms.

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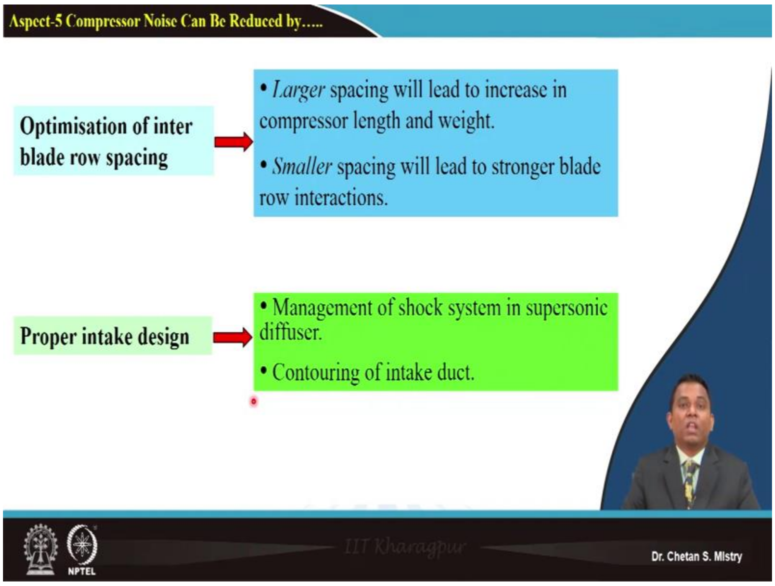

Now, after doing all this; next, that's what is of interest is to reduce the noise. Now, noise what we are talking of that's what has been addressed by two ways; one, that's what is optimize the inter stage spacing between rotor and stator, and next, that's what is proper intake design. Now, let us try to realize, suppose we have discussed when we were discussing about the length of the engine what we have realized, the space between this rotor and stator if we are increasing, that's what will lead to increase the length of the engine.

Now, if you will be having the largest spacing between these two, that's what we say, it will be increasing the length of the engine as well as weight of the engine. Here, the weight it means the length of the shaft that's what will be increasing. Do not take in sense of increasing number of blades, be careful. The smaller spacing, that's what will lead to say stronger say interaction of wake. We can say, we are having one rotating blade, one stationary blade. So, wake, that's what will be coming out from the rotor blade, that's what will be striking on the stator blade. And, that interaction, that's what will lead to have toner kind of noise, and that's what need to be addressed with. Now, for high bypass ratio engines, for fans, special kind of acoustic linings they have been provided near the casing region, that's what will be helping in reducing the noise.

Now, proper intake design, so the shock structure, that’s what we are getting in supersonic diffuser, that’s what need to be managed properly. Otherwise that may lead to give very high noise. And, this is what is not coming in the area of say compressor designer or engine designer. This is what is a special kind of application where airframe integrator, they are coming into the picture. So, when we are supplying this engine for airlines that time this airframe configure person, he needs to take care of this particular design. Same way, contouring of inlet duct. So, in order to have very good or say smooth or uniform flow at the entry, the inlet need to be designed in a proper way.

So, here this all what we are discussing in sense of addressing different aspects. This is what we say is in sense of improvement of our design. This is what is representing what all are the recent trends in sense of say addressing the most challenging part for say axial flow compressors which are applicable for, at this moment for, say gas turbine power plant. But the same logic, that’s what is also been applicable for industrial compressor as well as for industrial fans. So here, we are stopping with the discussion about what all are the recent trend, we will continue our discussion on some of the aspects in the next lecture. Thank you, thank you very much.