Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture 28
Selection of Design Parameters

Hello, and welcome to lecture 28. From today, we are starting with our Selection of Design Parameters module.

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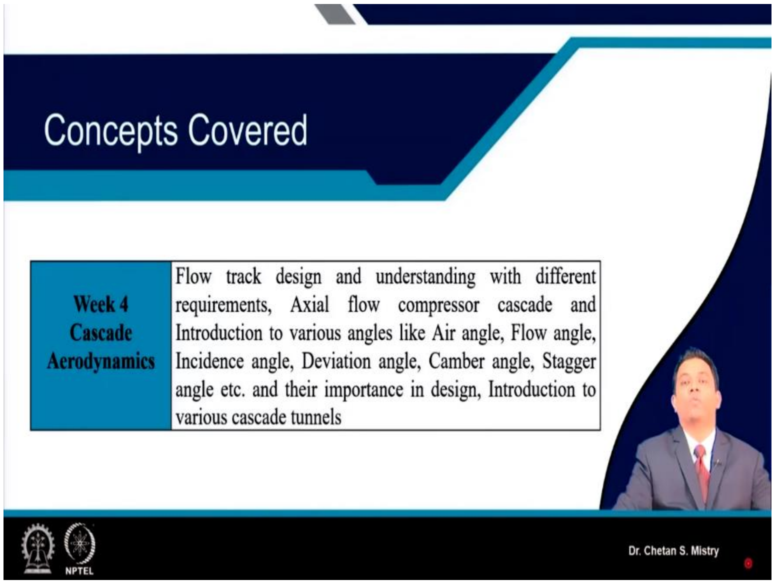

In last week we were discussing about very important aspects, which covers the flow track design and we have discussed different kinds of configurations which are possible for designing the flow track for axial flow compressor. Let it be LP spool, let it be HP spool. We have discussed about the constant tip diameter configuration. We have discussed about constant hub diameter configuration. We have discussed about constant mean diameter kind of configuration, we also have seen different kinds of combinations also possible.

This is what is very important when we are discussing the design of axial flow compressor; specially for say industrial compressor, for say Aero engine compressor as well as for say process industry compressors. When we are discussing about the industrial fans, where it may not come into the picture, but still this is what is very important and that is the reason why we have covered that in last module.

Then we were started discussing about the axial flow compressor cascade. So, in module 4 and module 3, we were discussing about the design aspects. Now, once we have done our all calculation for flow parameters based on our expectation, it is more important to consider different kinds of airfoils. So, in order to have that details, we need to have understanding of different airfoil parameters, that's what we have discussed with.

We have introduced the angles which are known as say incidence angle, deviation angle, metal angle, we have introduced say camber angle, stagger angle and we also have discussed what all are the importance of those angles. And for design how do we need to calculate those angles. Then, we started discussing about different kinds of cascade tunnels which are available globally and how do we use that data for our design purpose.

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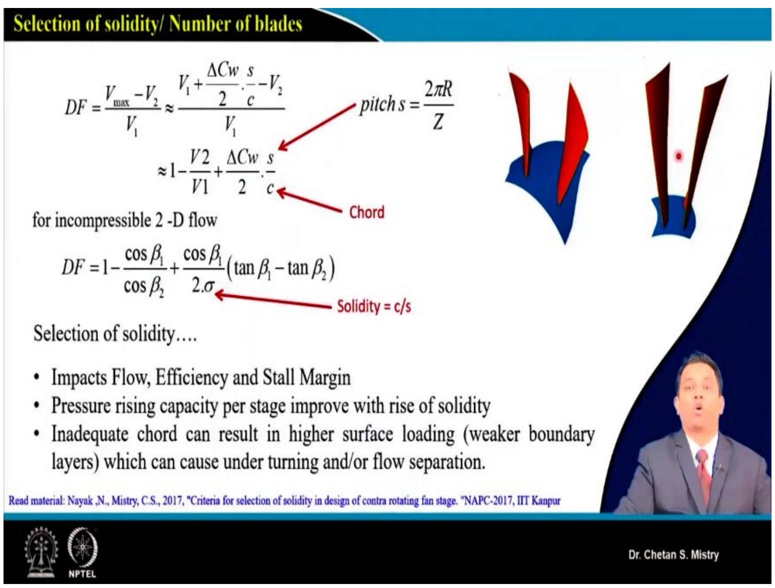

Now, let us start with the next module. So, very important part when we are discussing, that's what is coming with the selection of number of blades. When we say we are having gas turbine engines, this gas turbines engines, they are having application for aero engines, they are having application as we have discussed for say power plants, they are having application for the process industries, for all these compressors, we need to have certain constraints.

Mainly when we are discussing about the aero engines, that's what is very conservative in nature. The reason is we are having so many expectations from those gas turbine engines, and we are looking for those engines to work perfectly. Now, when we are talking about those engines application to aircraft, we are looking for as we discussed, we are looking for say compactness, we are looking for lightweight, we are looking for, you know, highly efficient engines with wider operating range. In order to meet such requirements, you know, per stage pressure rise expectation that will be increasing.

Now, when I say per stage pressure rise, that's what is increasing, means the stage need to do more amount of work and that is where our selection of parameter that's what is coming into the picture. So, first parameter or very important parameter that's what has been defined by Lieblien that's what we have discussed in our module that's what is called diffusion factor.

And that diffusion factor, we have realized, that's what is a function of my $\Delta\beta$ that means, what is my blade entry angle, what is my blade outlet angle, at the same time we have discussed the parameter called solidity; and solidity we have introduced as chord to pitch ratio. So, you know, the selection of this solidity that's what is very important, how it is important? Let us see; it has direct impact on my flow capacity. It has direct impact on the efficiency also it is impacting on the stall margin. So, these all are the prime requirements when we are talking about the application part.

When we say, the per stage pressure rise expectation that's what is to be higher that means the parameter what we say solidity that need to be higher. Now, when I say solidity need to be higher, we know the solidity it is a function of my chord and we can say pitch we have defined as say $\frac{2\pi R}{Z}$, Z is nothing but the number of blades.

So, now we are having two parameters that's what is very important for our selection; one, that's what is say number of blades and second, that's what is say my chord, okay. When we say chord, that need to have sufficient amount of length. So, if you recall in last module, we were discussing about the flow over say suction surface of our airfoil.

And we realized, we are looking for all the three regimes of our flow that's what is laminar flow, transition flow and turbulent flow. So, in order to have fully developed turbulent flow on the surface, we need to have sufficient amount of length that means, sufficient amount of chord for that particular blade, then only we will be having the flow what we are looking for.

Suppose, say if there is inadequate chord, then we will be having say higher surface loading, that's what will be giving, you know, your flow turning to be very large and that may lead to the flow separation. So, here if you look at, suppose this is what we can consider, say, here we are having the blade, that's what is having some chord and we are having say…some number of blades. And here, if you look at, we are having the height of the blade, that's what is larger compared to say by chord.

So, if we compare the working of these two, we can realize, here in this case, my chord length, that's what is sufficient in order to do the diffusion. When we are looking for this kind of blade where the length of the blade or height of the blade, that's what is larger, it may be possible that my chord may not be sufficient, and that is where it may be possible that we need to have consideration…design consideration that need to come into the picture. We can say, the flow passage, we should not forget all what we are discussing that's what is a diffusing passage, okay.

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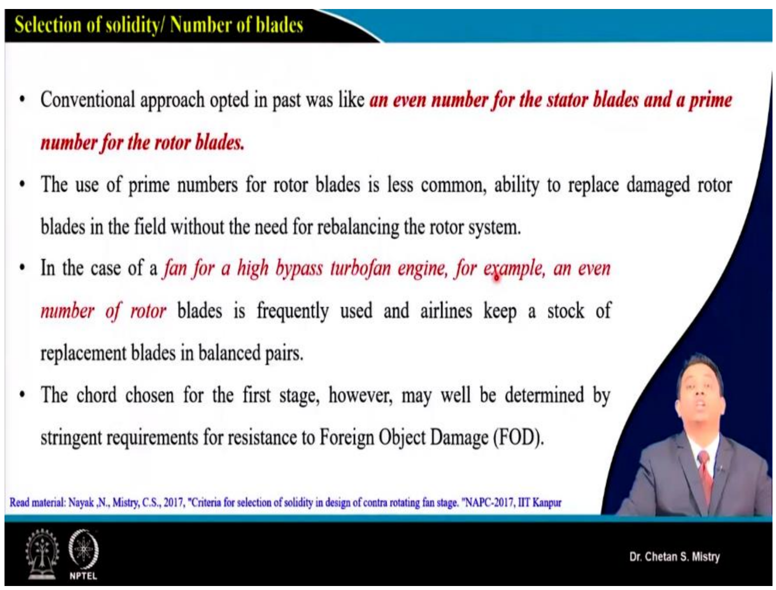

So, let us try to understand what all we are knowing and how do we use that knowledge. So, conventionally in past people used to select say, even number of stator blades and prime number of rotor blades. So, that's what was not that logical in that sense, but based on understanding, based on study, they people they have come up with this kind of configuration.

Now, the thing is, when we are talking about the prime number of rotor blades, in case of one of the blade that's what will be fail, then we need to replace that blade and that's what is required say maybe balancing again and that's what is time consuming process. If you are considering application for aero engines, where time also is a major concern.

So, in order to address this kind of issues for say high bypass ratio fans, this fan blades, this aircraft or airline companies, they are procuring in a set. So, suppose in case of failure of one of the blade, that's what will be replaced on both the side and that's what will be saving their time in sense of balancing.

So, you know, as such there is no specific rule in sense of selection of number of blades. But we will discuss like how people they are understanding for the selection of number of blades, because that's what is very important, when we are looking for other aspects. As we have discussed what chord we are selecting, suppose, if we are talking about the first stage, then I need to have sufficient length of that chord. So, that we will not be having any damage or say foreign object that's what to be striking of that blade, it should have sufficient strength. So, all these things that's what is giving the indication in sense of what need to be my chord and what needs to be by number of blades.

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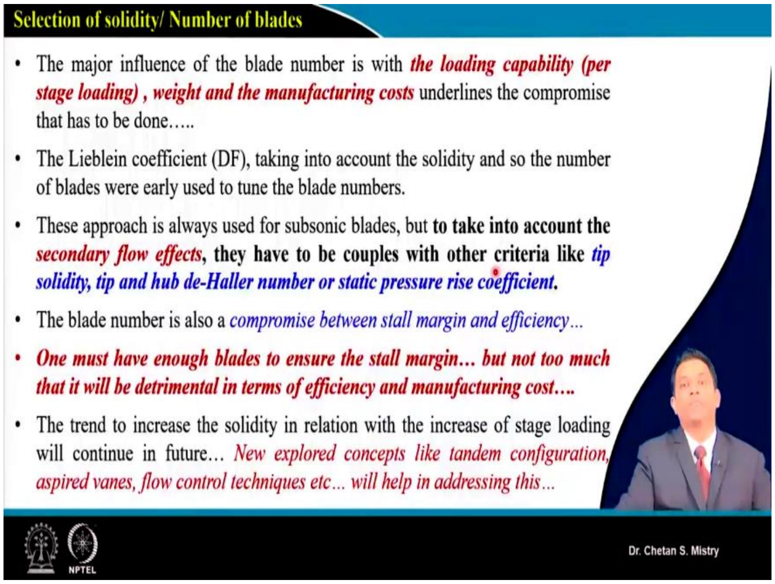

Here, if we consider say number of blades, then we need to realize what kind of loading we are looking for. That means per stage loading what we are expecting. Second parameter, that's what is coming into the picture is a weight of that rotor and because of the weight of that rotor, the weight of whole engine. Then we need to check for say manufacturing cost and we need to compromise in sense of all these parameters.

Let me put it here, suppose if we are talking about say industrial compressor which we are using for say power generation purpose. There we are having major concern that's what is the cost; there we are not having any constraints in sense of length of my engine. So, under that configuration, you know, your selection of number of blade that's what is not playing that major role, okay.

We can increase the number of stages, but when we are talking about the aero engine application, where we have restriction with the length, okay. Under that condition, we need to play with all this parameter that's what is say…blade loading, weight as well as the manufacturing cost. So, Lieblein parameter, that's what is giving us idea in sense of solidity.

And based on that as we have discussed, these days people they are taking this as one of the parameter. So, mainly at tip region, that diffusion factor, they are assuming. Based on that assumption, they are selecting the number of blades. Now, this number of blades, that's what will be decided with and then they will move ahead with the design modification, maybe they will stick with the same number or maybe based on computational study, maybe they will be modifying those number of blades.

But it says we need to take care of other parameters also along with the diffusion factor, that's what is taking care of our secondary flows; they are say tip solidity, then tip and hub de-Haller number and static pressure rise coefficient. So, there are so many parameters which are coming into the picture when we are discussing about the selection of number of blades, okay.

So, for first cut design, for the initial design, it is best way to select your diffusion factor or assume your diffusion factor and you can move ahead. As we will move ahead with the discussion in next module, we will be discussing what all are the other possibilities also for the selection of number of blades.

But at this moment just realize say diffusion factor that's what is giving me the understanding of what kind of loading or what type of loading we are expecting from particular stage, okay. So, blade number, that's what is a compromise between your operating range as well as your efficiency. Now, it says one must have enough number of blade to ensure the stall margin, but not too many blades that's what will be giving the detrimental effect on efficiency and manufacturing.

So, there it says you need to play with these numbers, okay. It says the trend for increasing the solidity in relation with the increase of the stage loading that's what is expecting some new kind of thought process. Let me tell you say new concepts like tandem configuration, aspirated vanes, active and passive flow control mechanism etc, now, we need to introduce. It may take time, but yes, this is what is now new demand, okay; and that's what will be helping us for addressing the few of the issue which we are discussing in sense of margin as well as in terms of say efficiency, okay.

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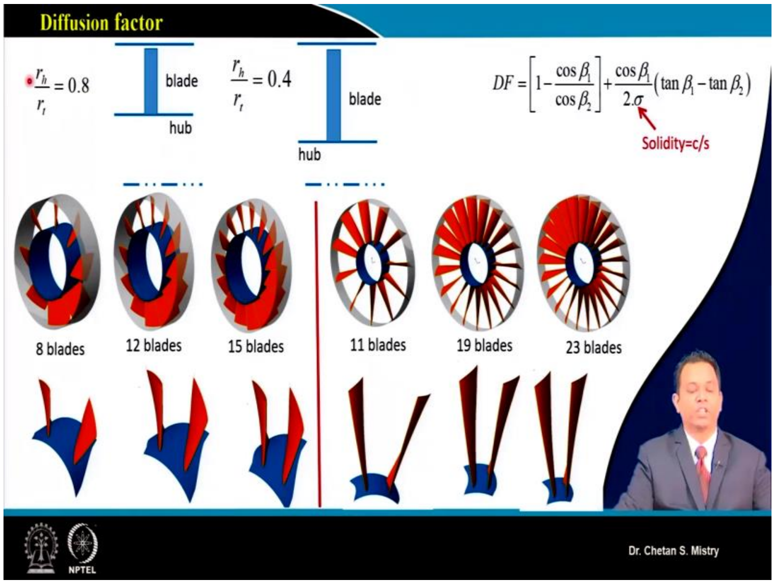

Now, here if you look at, we are having, do not get confused with the parameter here, this is what we are discussing in sense of radius ratio. Suppose, if I consider, this is what is my hub to tip ratio as 0.8 and here in this case we are having our hub to tip ratio as 0.4. So, we can say when we are having hub to tip ratio that's what is say 0.8 means we will be having shorter blades. Mostly for rear blades or rear compressor blades are of this kind.

When we are discussing the front stage or maybe for fans, they having this hub to tip ratio that's what is in the range of say may be point 0.4, 0.5, okay. Now, here this is what is representing, suppose if I consider, say…we are having 12 number of blades, okay; and suppose if I am considering that's what is having say, height to chord ratio, that's what is say 1, okay. Now, we are having the possibility as we have discussed, we would like to change our solidity or we say we want to increase our solidity.

When I say we are looking for increasing the solidity then we are having two possibilities; one, it is to increase the chord, second, that's what is to increase the number of blades or maybe you can go with both. But when we are going with both, you need to help compromise somewhere and that compromise as we have discussed, that's what is on our stall margin as well as on our efficiency.

Here if you look at, again do not forget, this is what all we are discussing in sense of making the defusing passage. So, here if you look at, we are having 12 number of blades, where will be going a little conservative and say we will be reducing the number of blades; but remember, by reducing the number of blades, my passage area, that's what is going to be large and it may not give what pressure we are expecting, okay.

So, the next option that's what will be coming with the increase of number of blades. So, suppose here, we are increasing our number of blades, yes, this is what will be giving you high pressure rise or what pressure rise we are expecting. But because of presence of more number of blades, the losses are going to increase; those losses are frictional losses, because of presence of more number of blades and that's what will lead to reduce your efficiency, okay.

Now, here in this case, suppose if you consider, say, here we are having our hub to tip ratio in the range of 0.4, okay. So, here if you look at, if I am putting my chord as constant, okay. So, chord as constant and if you are increasing our number of blades, then you can understand by increasing our number of blades, we are making our defusing passage to be narrower.

And that may give higher pressure rise, okay. But we need to realize one thing, what chord length we are selecting, that's what is very important. Because your chord needs to be sufficient to sustain your flow on the suction surface. We have realized all kinds of flow physics, that's what is happening on my suction surface and that's what will lead to change my C_p distribution of that particular airfoil.

When my C_p distribution, that's what is decreasing, you can say my pressure rising capacity at that particular station that's what is decreasing. In overall, we can say there is a reduction in pressure rise, okay, by that particular rotor or a rotor and stator combination or say for stage.

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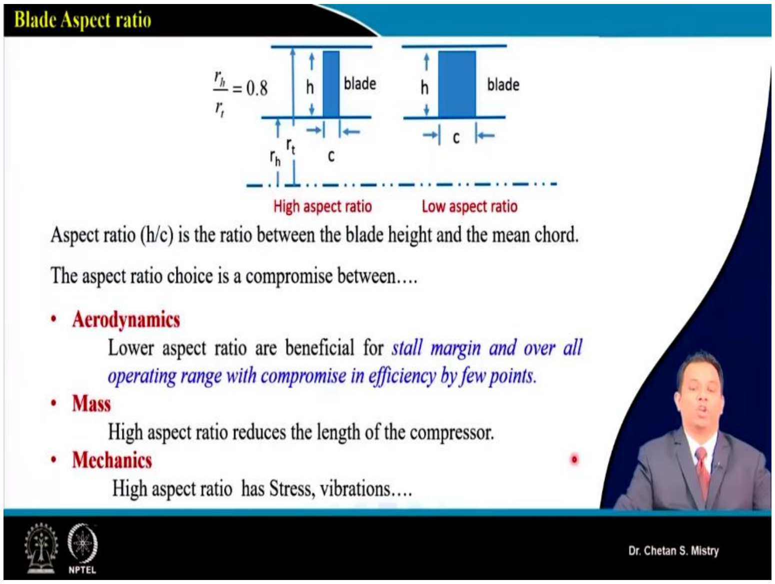

Now, let us see the other parameter that's what is coming into the picture; people they started talking about the aspect ratio. So, here in this case, this aspect ratio, suppose, if I consider say my radius ratio of 0.8, okay. So, be careful as I discussed earlier, my radius ratio and aspect ratio, they both are different thing.

Remember, we can have our radius ratio to be same, but we will be having blades with different aspect ratios. So, here in this case, if you look at, this aspect ratio is defined as

$$Aspect\ Ratio = \frac{height\ of\ the\ blade}{chord\ of\ the\ blade}$$

So, here in this case, if you look at my height is higher compared to my chord, we can say that as say high aspect ratio blade.

When I consider say my height to chord ratio, this height of my blade and chord, that's what is say lower or may height of the blade, that's what is lower or I say my chord of the blade, that's what is larger, we can say that as a low aspect ratio blade, okay. Now, this aspect ratio, that's what is very important for say our axial flow compressor, what we are using specially for aero engines, okay. Here in this case, we are focusing or our major focus, it is on three parameters. First, that's what is with the aerodynamics, second, that's what is with the mass and third, that's what is with your say mechanics.

So, when we say we are having this aspect ratio, so low aspect ratio blade, that’s what is giving benefit in sense of stall margin, and that’s what is increasing my overall operating range. Let me, tell this overall operating range is nothing but it is a region from maximum mass flow rate to minimum mass flow rate, okay; that’s what we say it is an operating range. So, when we are having say low aspect ratio blade, that’s what is giving us good stall margin, it is giving us higher operating range, but we need to compromise in sense of efficiency by few points, okay.

We will see what is the reason behind that, but you can understand, this lower aspect ratio blade, that’s what is having this kind of benefits. Suppose if I am talking about say mass, okay, so, for a high aspect ratio, it will reduce the length of my compressor. So, you can understand, suppose if I consider say high aspect ratio blades, that’s what will going to reduce my overall length of the compressor that means, that’s what will be helping us in reducing our mass, okay.

And next parameter, that’s what is with the mechanics, if you considers a high aspect ratio blade, you can understand my blades are taller blades, and that’s what will lead to give the focus of my stresses and vibration it is having issue with the aero elasticity. So, before 50’s and 60’s, most of the compressors or most of the engines, what we are looking for, they having the high aspect ratio blade.

Later on people they started talking in sense of low aspect ratio blade, there are major contribution by Wisler, there are major contribution by say Wisler. So, they people they have explored the possibility of using low aspect ratio blade and that is how this low aspect ratio blade that has come into the picture.

Because you can understand, again and again we are saying our major concern is with the safety and when we are saying say safety that means we are looking for a broader operating range, we are looking for say, you know, stall margin to be slightly higher. So, under that configuration, we need to think in sense of low aspect ratio blades, okay.

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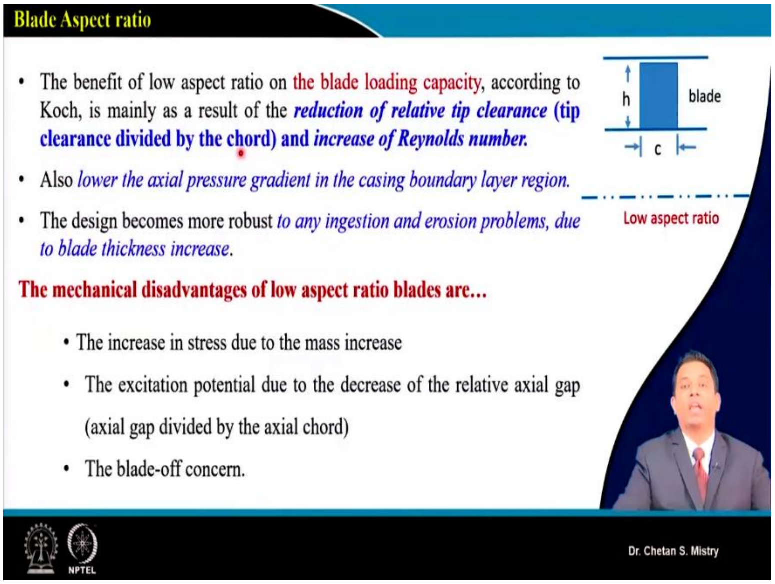

Now, let us see what all we learn for, a low aspect ratio blade, what it says? When we having a low aspect ratio blade, then it will be having higher blade loading. And according to Koch, it says we are having, so suppose, if I consider this is what is representing my low aspect ratio blade. So, the tip clearance, that's what we are defining in sense of t by h, we can say, that's what is the function of my height of the blade. So, you know, tip…of the…tip clearance by chord, that's what we will be coming to be lower in that case, okay. And again, when we are looking for say having wider chord, that's what is increasing the Reynolds number, okay.

When I say it is increasing my Reynolds number, that's what will lead to give my flow to be more turbulent on the suction surface and on the pressure surface and that's what we are looking for, okay. And that's what is helping us in sense of minimizing the chances of flow separation. When we say we are minimizing the chances for flow separation, we are minimizing the chances for stall and that is how we are improving our stall margin, okay.

Also, lower axial pressure gradient in the casing boundary layer that's what is a benefit of low aspect ratio blade and most importantly people they started talking, you know, it is more robust to ingestion and erosion problem. Because we are having our blade thickness that's what is larger. So, just understand, when we are discussing say airfoil the maximum thickness, that's what we are always defining in sense of chord, we say t by c ratio, so when I am increasing my chord, there automatically might the thickness of the blade that will be increasing, that’s what will lead to improve the thickness or say my radius at the leading edge.

Same way it is improving my radius at the trailing edge. So, all this, you know, now since we have understanding of compressor blade and compressor cascade, all these things we can co-relate and that’s the reason why module 4, it has been designed such that it will give more clarity for this kind of discussion, okay.

Some of the mechanical disadvantages of this low aspect ratio blades, they are say… it is… they are increasing the stress because of mass increase. So, you can understand, since we are increasing our chord, that’s what will lead to increase the mass of my rotor or mass of my stator, okay. Next, that’s what is the excitation potential due to the decrease of relative axial gap.

So, the axial gap between rotor and stator basically we are deciding based on percentage chord. So, that’s what is always a proprietary nature kind of work, but conventionally, people they are defining the axial gap between rotor and stator as percentage called of rotor, sometimes they are considering say percentage chord of average…of…chord of rotor and chord of stator, okay. And, there may be possibility that blade-off that’s what will be taking place, okay.

So, now when we are discussing low aspect ratio blade, we are having special kind of requirements for our case. Now, here in this case, if you recall when we started discussing about say engines, that time I was showing one of the engine, that’s what was Pratt and Whitney engine; I was showing one more engine, that’s what was say GE - Honda engine and if you recall, I was discussing for new coming engines people they are talking about wide chord blades. That’s what is because now our expectation in sense of operating range is increasing, okay.

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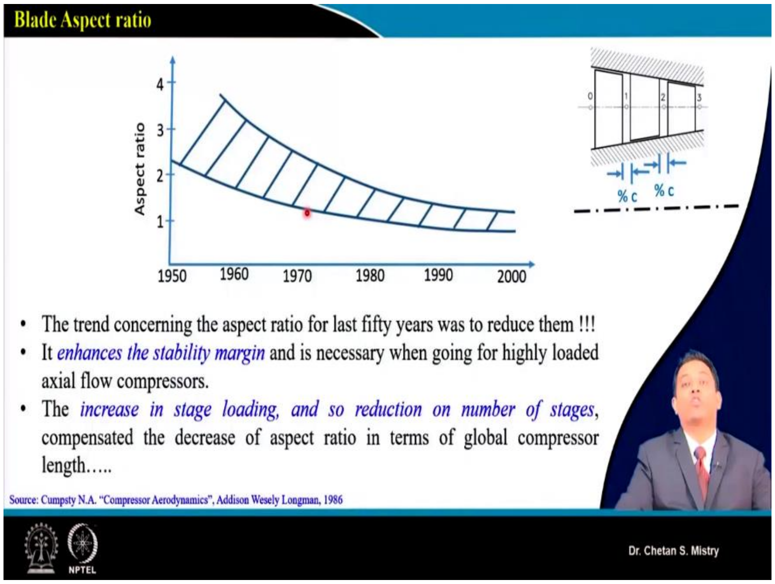

Now, if you look at this is what is a global trend. So, here if we consider, say…this is what is representing in 50's and this is what is during say 2000 and again, that's what is continue to get converge, okay. It says my trend for last 50 years that's what is to reduce the aspect ratio, okay. Because we are looking for enhancement of stability, we are looking for more and more highly loaded compressor, because we are looking for reducing the number of stages, okay.

We are looking for say compactness, we are looking for the lightweight, okay. So, the increase of stage loading and that is the reason why reducing say…the number of stages that will be compensated by decrease of aspect ratio and when we look at in global sense, that's what is reducing the length of our compressor stages, okay.

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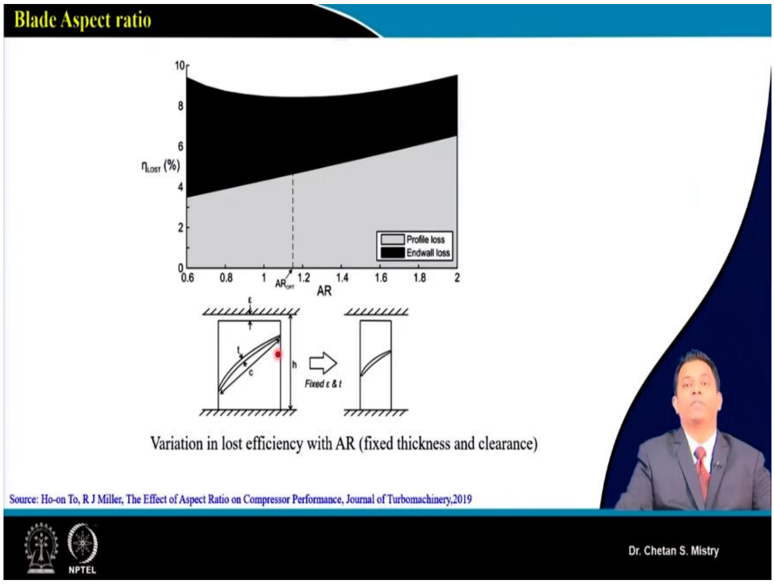

Now, this is what is one of the work, that's what is been reported by University of Cambridge. Now, whole concern, that's what is, how do we are what need to be the aspect ratio? So, for that case, what they have done, they have taken two different aspect ratio blades, they are having same thickness and same clearance, okay. So, here, if you look at, this clearance, and this clearance, that's what is same. And the thickness of the blade also they have considered to be same.

Now, earlier people, they were, say… judging or they were giving the reason for the selection of high aspect ratio blade, that's what is giving benefit in sense of reduction of endwall losses. And yes, that's what is, okay. But if you look at here, this is what is reported work, what it says when we are increasing our aspect ratio, we have our endwall losses, that's what is going to reduce, but at the same time, our profile losses, they are going to increase and this is what it says loss of efficiency.

So, we will be having say optimum range. Here this is what is coming 1.15; authors, they are recommending say 0.8 to 1.4 that can be the optimum aspect ratio, okay. So, if you recall in last lecture, we were discussing about the profile loss. So, you can co-relate what we mean by profile loss here, okay. So, this is also one of the indications why we are moving towards the low aspect ratio blade.

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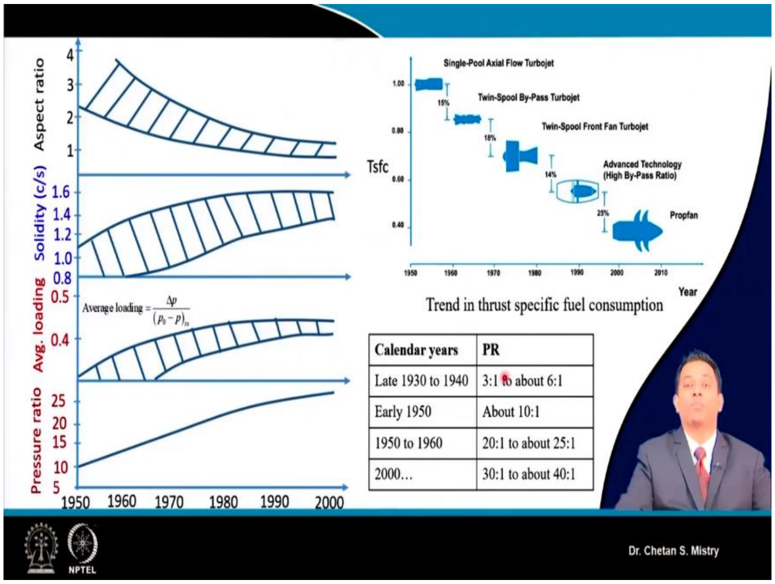

Now, just look at, this is giving what all we have discussed today. Now, if you look at, this is what is representing the global trend. So, here if you look at, say in 30's and 40's our expected pressure ratio was less. As per our requirement that's what has increased, our expectation in sense of transport purpose that's what has increased our pressure ratio. So, you can say over the year pressure ratio is almost reach to 40:1.

For most recent engine, the pressure ratio has reached to 64:1, okay. So, over the years, our expected pressure rise, that's what is increasing. At the same time, what we are looking for? We are looking for say average loading, per stage loading also we are getting improved. So, here if you look at, we are expecting per stage pressure rise to be higher and higher, okay. That's what is say over the, that's what is ranging on higher side.

And if you look at, this is what is representing in order to meet these two requirements, we are looking for higher solidity of the blades. So, this is what is representing we are moving towards higher number of solidity, okay. And at the same time, when we say solidity, that's what is corelating our chord and number of blades.

And if we look at, this is what is representing the trend for aspect ratios. So, over the year, people now they are preferred to move with say low aspect ratio blade and that's what is again and again, that's what is getting converge. So, you know, looking to this global trend with the expectation for future, we are looking for such kind of configuration.

Do not forget, say design of say axial flow compressor that's what was started long back; people they have done all kinds of designs. It is not that, that's what is the end of story, this particular plot, that's what is giving you idea how people they are thinking for future development of engines, what all parameters they are playing with in order to meet specific requirements.

Now, when I say specific requirement, just look at here, this is what is our requirement. What is our requirement? We are looking for our thrust specific fuel consumption to be lower. So, if you look at during 60's we were looking for that's what we have taken as the reference. The next expectation that's what has said like you need to reduce this thrust specific fuel consumption by 15 % that's what has given the new concept, that's what we say twins spool configuration.

Later, we are looking for reduction in thrust specific fuel consumption, it gives the idea about say, you know, having turbo fan kind of configuration. Later on, people, they are talking about high bypass ratio kind of configuration, then again people they started talking about say, turbofan or propfan kind of configuration.

Let me tell you, at recent, people, they started talking about ultra-high bypass ratio engine. So, this is what is running the whole business for gas turbine industries, specifically for the application of aero engines. Now, let me tell you what all people that are working for aero engines, slowly, that's what is been implemented even for land-based power plants, because there also our fuel consumption is of major concern.

People, they are looking for low cost engines, that's what we will be giving say, good improvement in sense of fuel consumption, and we are having restrictions with the pollution norms. So, in order to meet all such requirements, we need to have whole lot of research and development, still that's what is pending and we need to focus for the future. So, this is what is the end of our lecture. We will be discussing the next step in the next lecture. Thank you very much!