Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture 37
Design Low Speed Compressor

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Hello, and welcome to lecture 37. From today, we will be start discussing about Design of Low Speed Axial Flow Compressor.

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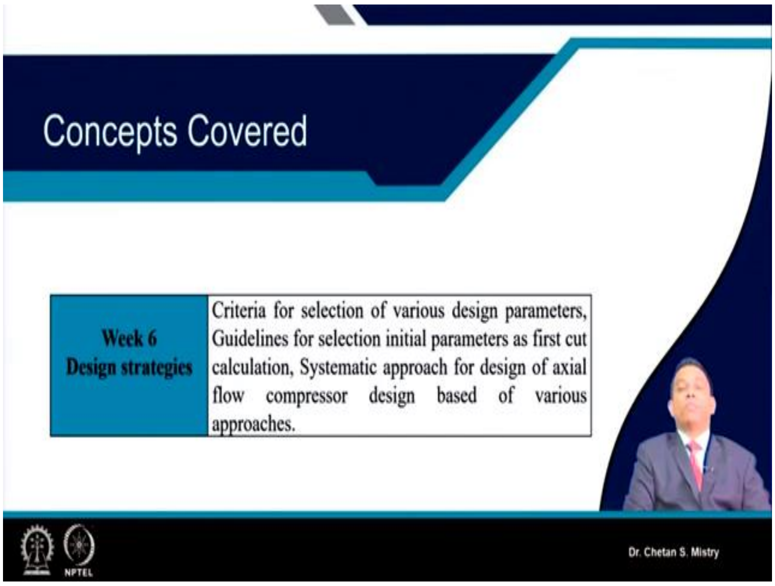

So, in last module, we were discussing about the criteria for the selection of various design parameters. We also were discussing about the guidelines for the selection of this initial parameters for first cut design, then we have discussed about the systematic approach for the design of axial flow compressor with different design approaches.

We realized, say if we are planning to design say…axial flow compressor for Aero Engines, they are looking for special kind of attention and that's what is starting with say basic cycle analysis, your gas turbine cycle analysis, thermodynamic cycle analysis; based on which, initial parameters in sense of mass flow rate, speed, efficiency, pressure ratio, temperatures, all those parameters we are calculating.

Then later on based on our expectation, we are planning to distribute this pressure ratio or overall pressure ratio in say maybe LP compressor and HP compressor and for that we are…we were deciding about the overall pressure ratio for say HP compressor as well as overall pressure ratio for say LP compressor. And based on that, we started discussing about the selection of say number of stages.

We also were discussing about different non-dimensional parameters called, say…flow coefficient, loading coefficient, pressure rise coefficient, all those parameters, they are of great importance.

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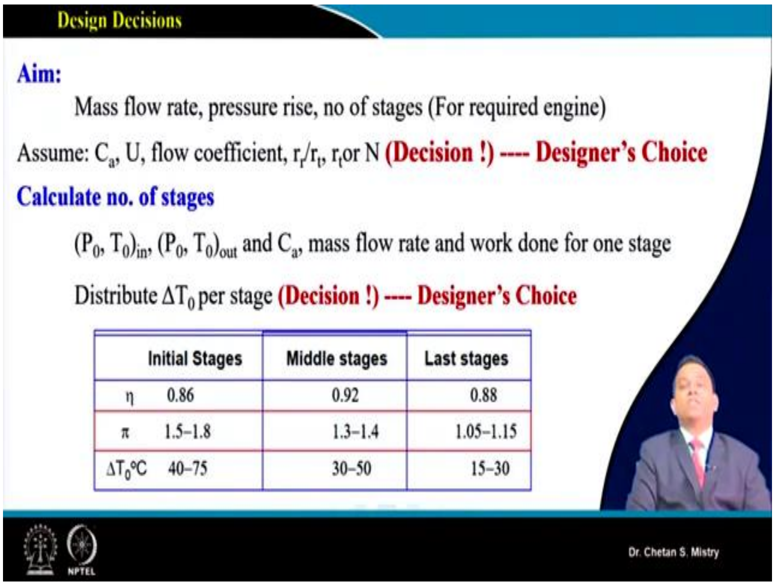

We started discussing about say very first part, suppose say if you are planning for designing say axial flow compressor for Aero engine, or say for land-based power plant; very first requirement, that's what is the mass flow rate. Suppose if we say for Aero engine, then my thrust requirement, that's what is a function of my mass flow rate. And that's what is of great importance.

So, that's what is a parameter which we need to decide with. Next, that's what will be overall pressure ratio, number of stages required. So, in order to calculate these parameters, we are looking for say axial speed, we are looking for say peripheral speed, we have defined a parameter called flow coefficient, radius ratio, casing, tip diameter, say rotational speed, all these parameters, they are coming under designer's decision.

Then very important part, that's what is to decide with the number of stages. And we were having good discussion about how do we decide with say number of stages. Once we have decided with our number of stages, we need to decide with say what will be the distribution of my pressure or pressure ratio and what will be my assume efficiency.

For that, we have discussed for our initial stage, we can say, we can expect higher pressure ratio from them. My efficiency, polytropic efficiency or per stage efficiency, we can say, for initial state that's what is say lower. And that's what we say around 86% and pressure ratio, we are expecting to be say 1.5 to 1.8.

Next, that's what is say your middle stages. And for that we have found my flow, that's what is flowing, it is more uniform in sense. And that is the reason why our expected efficiency will be in the range of 90 to 92%. And at the same time, our pressure ratio will be moderate in sense, say 1.3 to 1.4. When we are discussing about the later stages or the rear stages of our axial flow compressor, where our blades that will be having lower height, because of our compressibility effect, we can say, because of rise of pressure, our change of density which will be bringing change in our area. And that is the reason why those rear blades are shorter blades.

When these blades are shorter, there are more chances for having your flow to go three-dimensional and that is the reason why there we are not expecting more pressure rise; that number it is in the range of 1.05 to 1.15, okay, and efficiency will be in the range of 88%. So, initial first cut design, our assumption for the pressure ratio and efficiency, this is what will be giving us the idea.

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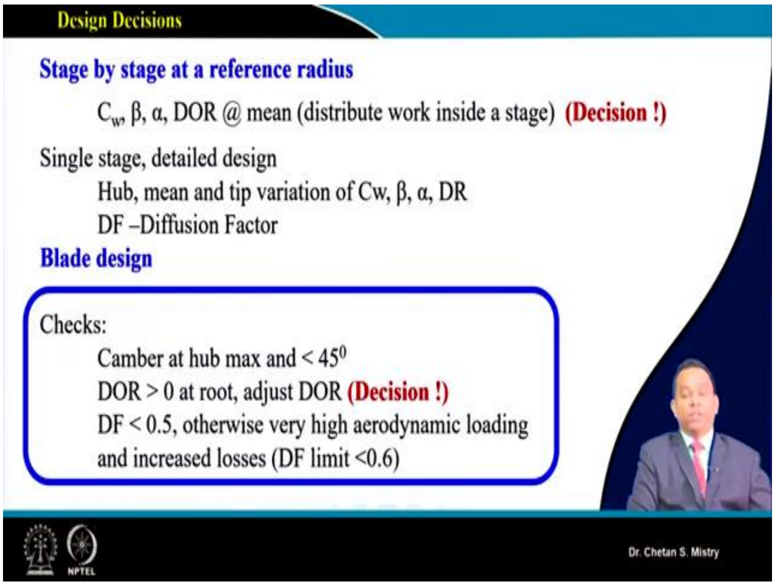

Then we have discussed about say calculation of different parameters, which includes say my whirl component, my blade angles, my flow angles, degree of reaction, diffusion factor, all those parameters, we are calculating at the mid-section and that's what is giving us an idea of what needs to be the work distribution along my span. Again, this is what is coming in say choice for the designers.

So, designer has to decide what all distribution he or she will be looking for. Once we are deciding with this part, we start designed with say single stage axial flow compressor for which we will be having say calculation of all these parameters at hub, mean and tip section. Then, systematically we need to divide our span into number of say sub-sections. And at all sub-sections, we need to calculate all these parameters. That's what we will be giving us idea how the blade of your rotor as well as stator will be looking like, okay.

Once this is what is done, say we will be reaching to the stage where we are having a blade that's what will be ready with. But before finalizing that part, some of the important clues, it says, like my camber angle at the hub, that's what will be going to be large because I will be having my $\Delta\beta$ to be large in that particular region. So, it says try to avoid this camber angle to go more than 45°.

Next parameter which we need to keep on eye, that's what is our degree of reaction. So, if we say our degree of reaction to be 0 or say negative, that's what you need to avoid. And that's what is a designer's choice how to modify the section, particularly this kind of situation is happening near the hub region, okay.

So, designer will decide how do we manage the degree of reaction within our require range or say assume range. One more parameter, as we have discussed, that's what is say diffusion factor, this diffusion factor that says like it should not be more than 0.5, but for most modern design, if you look at, we are having degree of reaction, that's what is going in the range of 0.6.

So, when we start doing our design, that time we will be keeping on eye; so, there is some guidelines, that's what is available with us. So, we will be started doing these and based on these guidelines. Then after we will be verifying whether we are meeting with our expectations or not and accordingly based on the requirement, we need to modify certain parameters but the initial guess that's what is very important.

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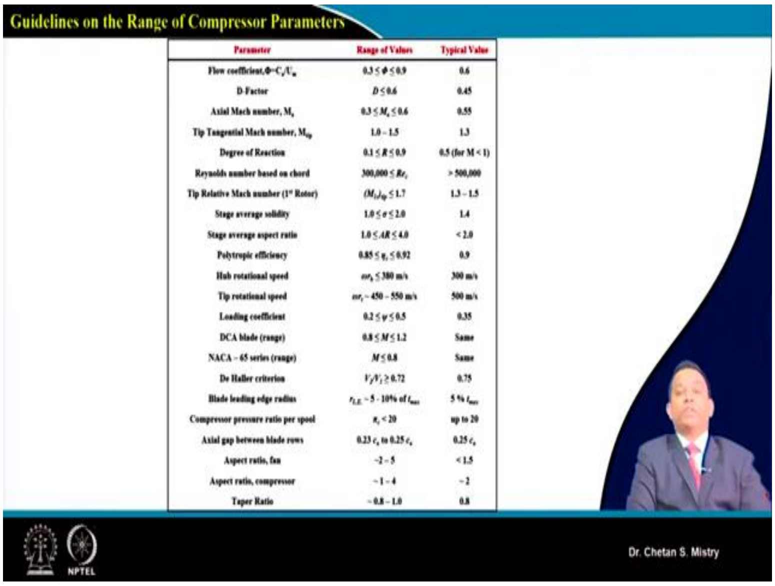

Parameter	Range of Values	Typical Value
Flow coefficient, $\Phi = C_x/U_m$	$0.3 \le \phi \le 0.9$	0.6
D-Factor	$D \le 0.6$	0.45
Axial Mach number, M_x	$0.3 \le M_x \le 0.6$	0.55
Tip Tangential Mach number, M_{tip}	1.0 – 1.5	1.3
Degree of Reaction	$0.1 \le R \le 0.9$	0.5 (for M < 1)
Reynolds number based on chord	$300{,}000 \le Re_c$	> 500,000
Tip Relative Mach number (1st Rotor)	$(M_{1r})_{tip} \le 1.7$	1.3 – 1.5
Stage average solidity	$1.0 \le \sigma \le 2.0$	1.4
Stage average aspect ratio	$1.0 \le AR \le 4.0$	< 2.0
Polytropic efficiency	$0.85 \le e_c \le 0.92$	0.9
Hub rotational speed	$\omega r_h \le 380$ m/s	300 m/s
Tip rotational speed	$\omega r_t \sim 450 - 550$ m/s	500 m/s
Loading coefficient	$0.2 \le \psi \le 0.5$	0.35
DCA blade (range)	$0.8 \le M \le 1.2$	Same
NACA – 65 series (range)	$M \le 0.8$	Same
De Haller criterion	$V_2/V_1 \ge 0.72$	0.75
Blade leading edge radius	$r_{L.E.} \sim 5 - 10\%$ of t_{max}	5 % t_{max}
Compressor pressure ratio per spool	$\pi_c < 20$	up to 20
Axial gap between blade rows	$0.23\,c_x$ to $0.25\,c_x$	$0.25\,c_x$
Aspect ratio, fan	~2 – 5	< 1.5
Aspect ratio, compressor	~1 – 4	~2
Taper Ratio	~0.8 – 1.0	0.8

Some of the guidelines, that's what is given, some parameters it is defined in open literature they say like my flow coefficient that needs to be in the range of 0.3 to 0.9 and preferred value it is say 0.6. This flow coefficient, as we have discussed earlier, that's what has been defined sometimes in the form of midsection, sometimes people, they are taking at the tip section. So, you need to be careful about that number.

Next as we have discussed, our diffusion factor should not be more than 0.6; it is preferred that if we are maintaining this diffusion factor in the range of 0.45 for our design case. Axial Mach number, that's what is at the entry of our stage, that need to be in the range of 0.3 to 0.6; it is preferred that like 0.55 it is okay kind of number. Degree of reaction, as we have discussed, that's what is varying from 0.1 to 0.9; it says for say subsonic kind of compressor, we will be going with say our degree of reaction in the range of 0.5.

Reynolds number, that's what is very important in sense of all kinds of aerodynamic losses, those are happening on the suction surface and that's what is responsible for say flow separation and stalling. That is the reason why this is what is very important parameter. It says based on my chord, that number need to be, you know, that need to be in the range of say 3 lakhs, okay. And preferred number, that's what is less than 5 lakhs.

Now, Relative Mach number, that's what is say in the range of 1.7; it is preferred you will be going with say 1.3 to 1.5 it is okay kind of number. Stage solidity, that need to be in the range of 1 to 2; preferred value that's what is 1.4. Stage aspect ratio, as we have discussed, there is a trend for going for say low aspect ratio, we have seen over the year people, they have preferred to go with say low aspect ratio kind of design.

So, which stage we are designing, based on that we need to decide with this aspect ratio; it says preferred, that's what is if you are going with say more than 2, it is preferred for that. Now, in sense of efficiency, as we have discussed, the polytrophic efficiency, it is very important; we have discussed about say different stages that need to be vary in the range of 0.8 to 0.9.

So, we can say, we have discussed for say our middle stage, we are considering that to be 92%; for say initial stage, that's what is say 85%; or later stages, we are assuming that to be 88%. So, that's what we need to take care of. The loading coefficient that need to be in the range of say 0.2 to 0.5; it says preferably if you are going with 0.35, it is okay.

Now, DCA airfoil, when we are using, that's what is say our flow or our Mach number, that's what is in the range of 0.8 to 1.2. It is to prefer to go with say DCA kind of airfoil; when we are having say Mach number, that's what is less or equal to 0.8, we can go with the NACA 65. De-Haller's number, we have discussed that need to be more than 0.72, 0.75 it is a good number for that case. My leading-edge radius, that's what needs to be in the range of 5 to 10% of my thickness of the airfoil.

Now compressor pressure ratio per spool, it says that need to be less than 20, up to 20, that's what is preferred. So, these days, we are talking about say high overall pressure ratio kind of configuration. So, there this number may be varying in sense of requirement. The axial gap between say rotor and stator, it says, it need to be in the range of 0.23 to 0.25 of axial chord; it depends which kind of compressor we are designing, okay.

Aspect ratio as we have discussed, for the fan, that need to be in the range of 1.5. We are compromising somewhere in sense of efficiency, but that's what is increasing our overall operating range and overall pressure rise. So, that is where, it is preferred to go with say aspect ratio for fan in the range of 1.5. Taper ratio, that's what is defined in sense of my chord at hub and chord at the tip, and it is preferred that we will be going with the tapper ratio of 0.8.

So, this is what is giving us idea about what all parameter we can initially guess with. There are so many ideas behind design of axial flow compressor, it varies from company to company, it varies from designer to designer, and it varies based on the experience and available computational and experimental tools.

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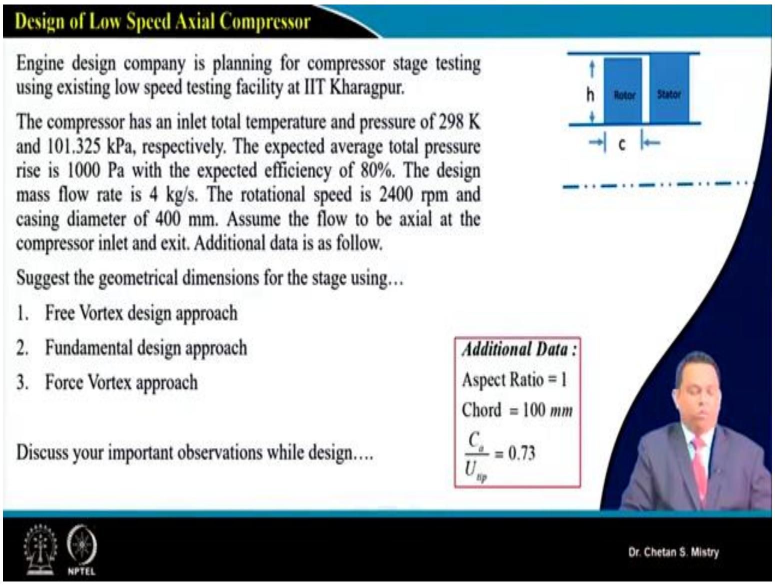

Now, let us see, we will start with the design of say low speed axial flow compressor. So, this is what is the data, that's what is available with us. So, engine design company is planning for say compressor stage testing using existing low speed testing facility at IIT Kharagpur. The compressor has inlet temperature and pressure of 298 Kelvin and 101.325 kPa, respectively.

The expected average total pressure rise is 1000 Pa with expected efficiency of 80%. The design mass flow rate is 4 kg/s, the rotational speed is 2400 rpm, and casing diameter is 400 mm. Assume, the flow to be axial at the entry of the compressor and at the exit of the compressor. The additional data, that's what is given, it says, my aspect ratio for the blade it is 1, chord is 100 mm and C_a/U_{tip} that's what is 0.73.

Now, suggest the geometrical dimensions for say stage using free vertex design, fundamental design approach and forced vertex approach. Discuss your important observation while doing the design. So, we will be taking this data for say our design for low speed axial flow compressor.

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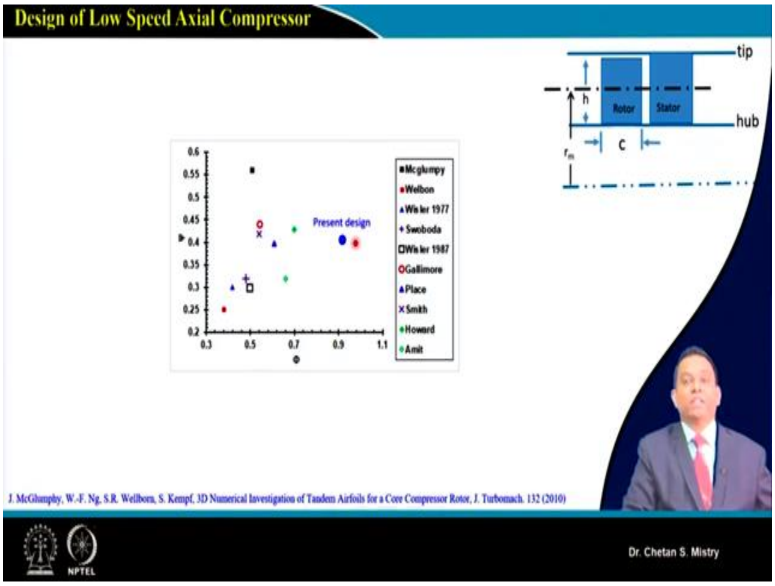

Now, let us look at what all it is a meaning of that. So, this is what is representing $\phi\ vs\ \psi$ plot. That's what has been taken from McGlumphy's paper, it says different high pressure rise or high total pressure kind of configuration, they are available for say different ϕ and ψ. So, these are some of the data, that's what is available. Here, for our compressor, our data, that's what is lying here, where we are having our flow coefficient to be larger and are pressure rise coefficient, that's what is in the range, okay. So, we are going to design for this particular stage.

Now, we have taken these data, that's what is for specific reason. Now, let us try to understand why we are doing design for this low speed axial flow compressor and why this company, they are planning to do their testing here.

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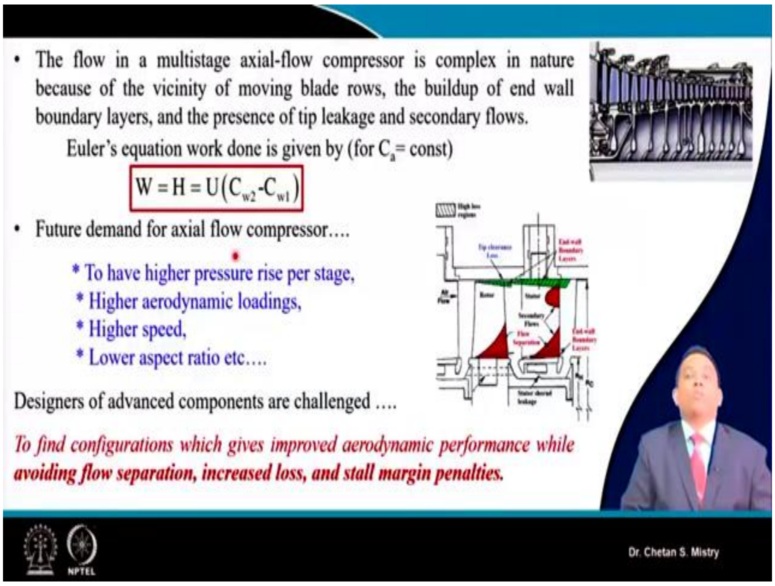

So, what we learn, what all we know, we are having multistage axial flow compressor, in which because of my rotation of the wheel, we are having say growth of boundary layer near the end wall region, we are having the presence of tip leakage flow, we are having the presence of secondary flow, all these, that's what is making my flow through axial flow compressor to be very complex and three dimensional. What we know from our fundamental, that's what is say using Euler's equation, it says my work done, that's what is a function of my peripheral speed and ΔC_w, okay, that's what we are defining in sense of our tangential velocity component or whirl component.

Now, we started discussing about so many aspects for the future requirement, what are our future requirements? It says we are looking for high pressure rise per stage, we are looking for higher aerodynamic loading, we are looking for high speed, we are looking for low aspect ratio blade, these all, they are related with our requirement of improvement in specific fuel consumption.

So, we are looking for compact machines, lightweight machines, which will be reducing our weight and drag that's what will be helping us in sense of improvement of fuel consumption. Even we are looking for wider operating range. So, all these requirements, that's what is coming into the picture.

So, you know, it is very challenging, because when we are going with such kind of expectation, we will be having difficulties in sense of flow separation, we will be having difficulties in sense of having rise in losses means we will be having loss of efficiency, we will be having say stall margin as a penalty. So, this is what we are looking for in sense of our improvement, okay. Now, when we are expecting this kind of thing, that's what is different from what already existing compressors they are having, okay.

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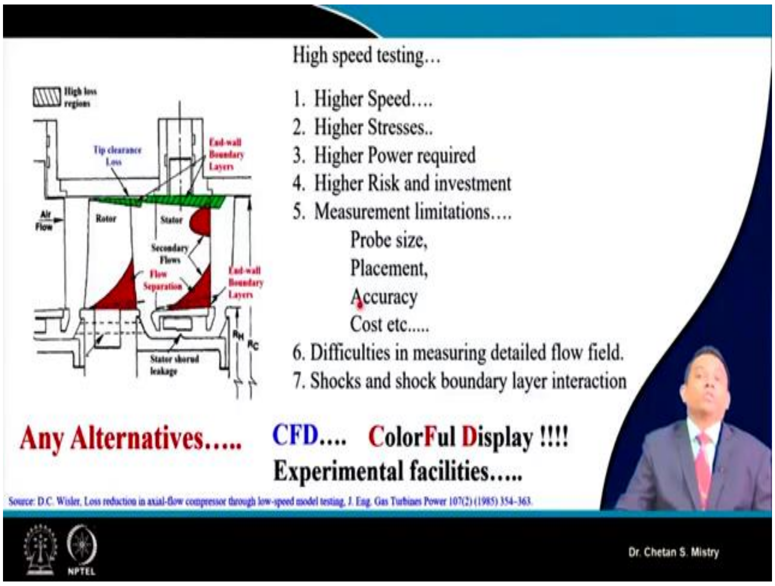

So, let us try to look at what all is the meaning. So, this is what is a diagram, that's what was given by Wisler. So, here if you look at, this is what is say my rotor and stator, this is what is representing what is happening near my hub, we are having close separation that's what is happening near my hub for the rotor as well as near say stator also. Similarly, we are having say tip clearance loss, we are having end wall boundary layer, and as we have discussed, that's what is giving more complexity to my flow and this is what will lead to increase the losses.

Now when I say increase in losses, we are expecting our efficiency to be higher that means we need to minimize these losses, okay. So, for all this purpose, we need to go for systematic testing. Now when I say testing, my compressor for HP spool or HP compressor, that's what we will be rotating at high speed maybe 12,000 to 18,000 RPM. Same way if you are looking for say LP spool, though it is rotating at low speed, my diameter is larger, okay.

So, suppose say, we are discussing about say high spool or say high pressure rise compressor, we know that's what is the heart of the engine we have discussed about that part. So, if we are looking for testing for such kind of compressors, then we need to go with the higher rotational speed, same as my engine speed, that's what will lead to higher amount of stresses; mechanical stresses will be increased, higher power requirements that may be going in the range of megawatts, okay. At the same time, that's what is increasing our risk as well as the investment.

So, you can understand, suppose if it is rotating at very high speed and you are doing your testing, that means it is a little risky to handle this kind of situation, okay, in laboratory. Now major challenge that's what will be coming is in sense of measurements. So, in order to measure our velocity components, in order to measure the pressure, in order to measure the flow angles, for that we are using say probes; that may be multiple probes, or maybe say hot wire probes.

So, when we are using that, then because of presence of these probes, that's what will be acting like obstruction to my flow. And that's what lead to change my flow physics within my flow passage. And that too, if it is say high speed, you can understand, my flow physics that's what will be changing drastically because of presence of my shocks, okay.

Then, where do we place, say the space, that's what is available, that may be one of the constraints. The accuracy, because you can understand, suppose my rotor is rotating at 15,000 RPM, my per blade moment if we are measuring, that's what will be coming in the sense of microseconds or nanoseconds, like you need to have those data acquisition systems which will be capturing all this flow physics, okay. Then, the cost criteria, that's what is coming into the picture.

Now, we are more interested in what is happening in sense of flow field, we can say, detailed flow field study. Suppose say, we are looking for what is happening between two rotor blades, what is happening between two stator blades, such kind of detail flow field measurement, that will be very difficult when we are talking about this high-speed kind of configuration. The very big challenge that's what will be coming is in sense of shocks and shock boundary layer interaction, okay.

So, if we consider, we need to find for other alternatives, what all are the alternatives? One alternative straightway will come it says maybe we will be using our CFD tool or we can say, we can go with say experimental facilities. Now, when we are talking about the experimental facilities, we have seen this all are the challenges we are having for such kind of compressor.

When we say our CFD, that's what is more or less we can say in sense of colorful display. Sorry for that, but you can understand unless and until your CFD simulations, they have been validated with the experimentation, that simulation has no value. And when we are talking about application to aero engine, where we are very particular, we are very specific, few point variation that has more impact in sense of what all we are expecting.

So, that is the reason why now, you know, challenge that's what will be coming is you need to go with more in sense of experimentation. Even for your validation for CFD, you need to do your experimentation. Now, suppose if you are looking for say, companies, they may go for, say this kind of experimental facility, that is not a big deal; but at the same time, they are more involved in research, development, fabrication, testing, all those activities. So, now, what will happen, the work that will go to someone else.

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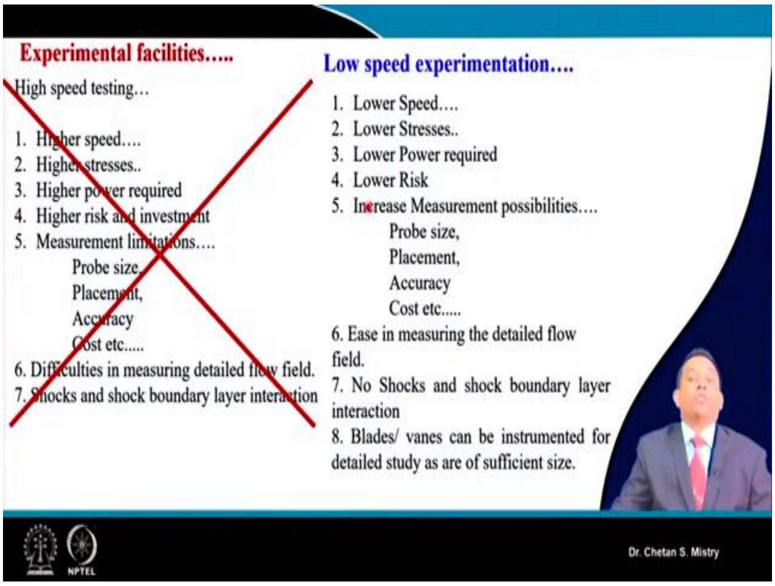

So, if we look at, say this is what we are looking for, say this work that will go to universities or maybe some research centers. Now, when we are talking about the universities, this all what we are discussing, that's what will be very challenging. So, we need to have the solution for this problem. What is the solution? It says, we need to go with low speed experimentation.

When we say low speed experimentation, my rotational speed will be lower. That's what will be having say lower stresses, power requirement also will be less, our risk factor, that's what is less compared to our high-speed configuration. When we say increase the measurement possibilities, because now we are having some kind of flow, that's what easily can be captured by using these probes of specific dimensions.

We can put them in a flow domain as per our expectation. We will be getting data in more accurate form. And cost also will be coming in sense of reduction. We can say, we can go with say detailed flow fill measurement, no shock and shock boundary layer interaction, that's what is a benefit of going with say low speed compressor facility.

And, we can even use blades or vane, they may be instrumented in order to study that detailed flow field, okay. And that too with the sufficient size, when we are talking about my flow Reynolds number, that's what is one of the criteria where we will be having such kind of low speed facility, that's what will be helping us in sense of achieving what we are looking for.

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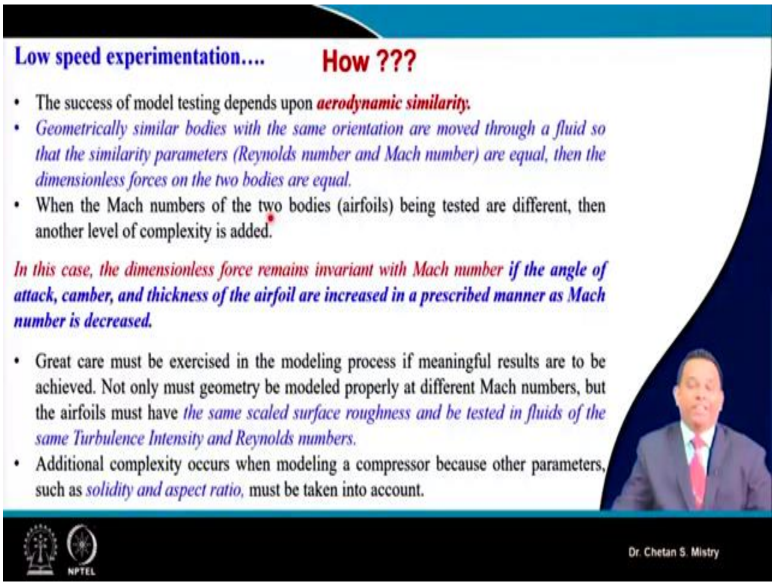

So, now the question will come. Yes, we have solution for low speed testing facility. But the question is, how do we address this? How do we arrange or how do we go with? It says, the success of this model testing, that's what is depending on my aerodynamic similarity, okay. So, it says geometrically similar bodies with the same orientation are moved through a fluid, so that similarity parameters named say, Reynolds number and Mach number are equal, then dimensional forces on these two bodies are equal.

So, we can understand, we are having two parameters, that's what we need to be checked with; one, that's what is say Reynolds number and second, that's what is say Mach number. When we say Mach number, then you know, that's what is giving additional complexity, because we can understand when we are talking about Mach number, if my flow is going transonic or supersonic, my flow structure, my flow field, that's what will be different.

What it says in the case, dimension parameter…dimensionless parameter remains invariant with the Mach number if we arrange the angle of attack, camber and the thickness of the airfoil as increase of you know, address of change of my Mach number, okay. So, the situation is supposed if you are considering our suction surface of the airfoil; now, in…on suction surface, we have our acceleration of our flow, that’s what can be modified in order to meet the requirement of such numbers, okay.

The great care must be exercise in modeling the progress if the meaningful results are to be achieved. Not only the geometry, but we need to take care of surface roughness, we need to take care of turbulence intensity, we need to take care of Reynolds number. Along with that, we are having more complexity in sense of solidity and aspect ratio. So, these all parameters, that’s what is bringing more challenge in order to what we are thinking of in sense of having aerodynamic similarity.

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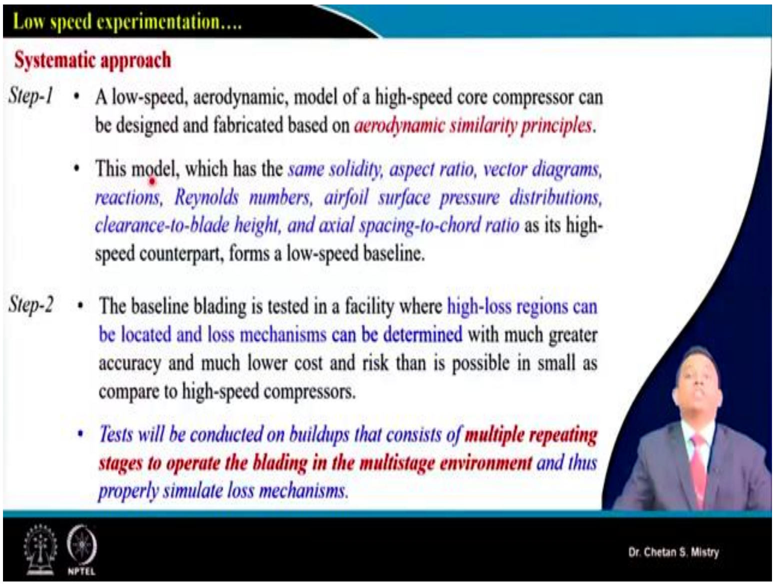

But at the same time, as proposed by Wisler, say, the low speed aerodynamic model of high speed core compressor can be designed and fabricated using your aerodynamic similarity principle. This model which has same solidity, aspect ratio, vector diagram, reaction, Reynolds number, surface pressure distribution, clearance to blade height, axial spacing to chord as same as our axial speed compressor, say high speed compressor and low speed compressor, that’s what we need to manage with.

Now, once we are doing this similarity, then we will be finding the high loss region and that’s what will be helping us in sense of identifying the location where the losses are major. With low speed or low cost and low risk, we are able to find the locations or we are able to find these losses which that can be applicable or maybe we will check for multi-stage axial flow compressor for high speed configuration.

Now, the challenge here, it says, the test will be conducted on built off of that's what is consist of multiple blading stage to operate the blading in a multi stage environment. So that, we can simulate that in proper way to identify the loss mechanism. So, what low speed configuration we are discussing, that's what is need to be conducted for say multistage configuration.

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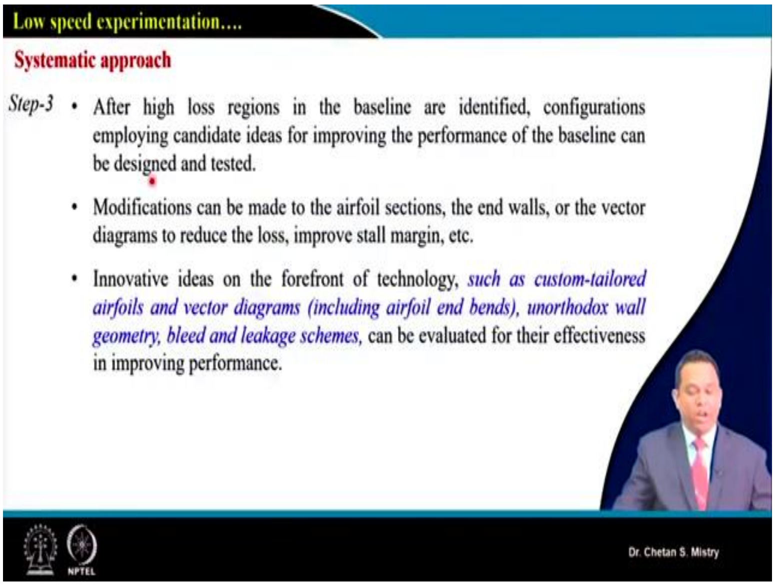

Now after this loss mechanism or loss formation, that's what we have identify, then we can modify our design as per our requirement in order to address the losses to be minimized, and that can be tested. This modification, that's what will be in the sense of say maybe airfoil section, end walls, vector diagram, that's what we will be increasing or changing my stall margin.

Maybe we can go with the innovative ideas, as we have discussed earlier, say custom tailored airfoil, vector diagram where you will be having airfoil end bends, say unorthodox wall contouring, bleed, leakage scheme, all these can be tested and checked with. In order to check the effectiveness and the improvement what we are expecting with.

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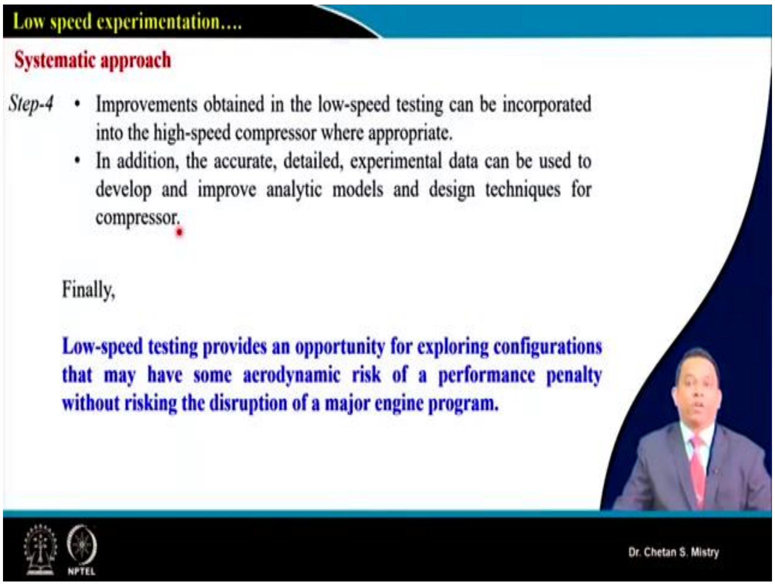

Now, these improvements, that's what is once we have achieved, that can be incorporated in sense of say, high speed configuration. So, accurate, detailed experimental data that can be used to develop and improve your analytical model and maybe for the future design techniques. Finally, what all we are getting, that can be used with say minimum…say…risk in sense of aerodynamic penalty. At the same time, that's what is not affecting our ongoing design program or say major engine design program.

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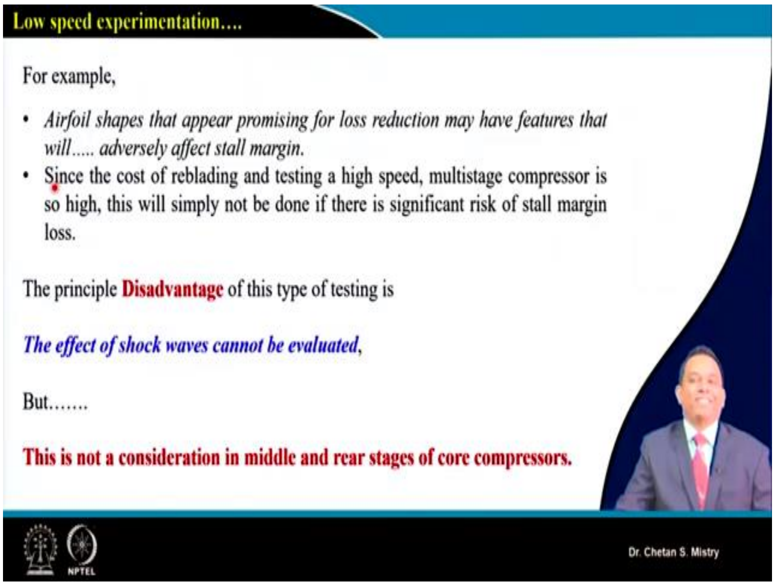

Now, what happened? Say, you know, like in sense of airfoil shapes, that's what is appear to be…showing the improvement in performance, it may be adversely affecting our stall margin, it may be possible, okay. Since, we are having our costing for making of this blade, that's what is lower. So, we can go with say multiple configurations, we can go with say number of blade, rotors and stator that can be modified and tested, that's what may not be possible with say your high speed configuration, because it will be expensive affair.

But what happens if we are doing all this kind of situation? This is…the initial or say finally, the question, that's what will be coming what all are the disadvantages? It says, the effect of shock waves cannot be evaluated, okay. But, we need to understand, this is not the consideration in middle or the rear stage of our core compressor.

So, what method we are discussing in sense of our aerodynamic similarity or say transition or formation of experimental facility from high speed to low speed transformation, that's what can be safely been used when we are discussing for the design of say HP compressors, okay. So, there are more details, that's what is available in open literature; many universities, many companies, they are exploring this possibility; there are many experimental facilities which are available globally in order to do such kind of testing.

Now, the question will come what all data we are achieving by having say low speed testing, that needs to be transformed in say high speed configuration. And, that's what is more challenging. A person, who is involved with that kind of work, he need to have detailed understanding. Here, my geometrical parameters, geometrical similarity, aerodynamic similarity, those all terms, they are coming into the picture.

So, many times what all results we are achieving, that will be non-dimensionalized in the form and that can straight away be used for high speed configuration. So, this is what is possible and universities and engine making company, they are together they are working on these aspects, okay.

So, in order to have that kind of understanding, we have taken the numerical. So, in next lecture, we will be discussing how do we go with a design of low speed axial flow compressor for such kind of requirements.

So, thank you very much for your kind attention! I am sure, this, what we have discussed, that will be helpful to you in sense of understanding, do not consider that what all we are doing at the university level for say low speed testing it is of no use, this data they are of more importance. Those who are matured enough. They know how to use this data for the future developments! Thank you.