Aerodynamic Design of Axial Flow Compressors & Fans
Professor Chetankumar Sureshbhai Mistry
Department of Aerospace Engineering
Indian Institute of Technology, Kharagpur
Lecture 43
Design of Low Speed Contra Rotating Fan

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Hello, and welcome to Lecture 43. From today, we are going to start our new module, that's what is say for design of low speed contra rotating fan.

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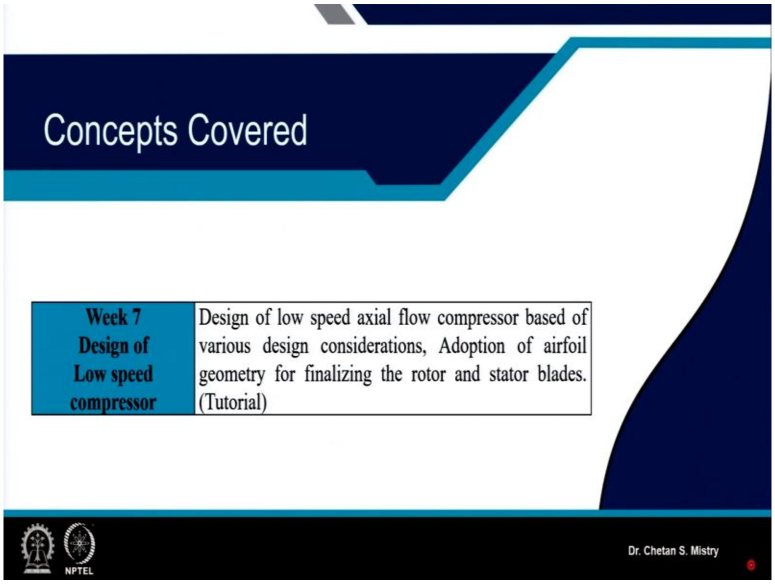

In last module, we were discussing about design of low speed axial flow compressor. In that module we have discussed what all are the need of this low speed configuration and why the research that’s what is going on in universities using say low speed test rigs available with them. Then, we have taken one of the numerical for design of low speed axial flow compressor using free vortex concept, using fundamental approach and by using say forced vortex concept.

And I am sure you might have done your calculation, pen paper calculation, you might have developed your own excel design sheet based on what all we have discussed up till now. We also were discussing about say kind of airfoils what we have used, how to develop those airfoils, how to stack those airfoils, and then after how to incorporate your stagger angle in order to make the blades. And that’s what will give you the confidence for say design of low speed axial flow compressor.

Now with these fundamentals let move with say new kind of concept in sense. We say it is a new concept but earlier people, they have explored, and based on their experience they tried to incorporate new fundamental approach for the design, and that’s how the new development that’s what is going on. The question may come like what is the need, why we are having contra rotating fan kind of configuration or contra rotating axial flow compressor?

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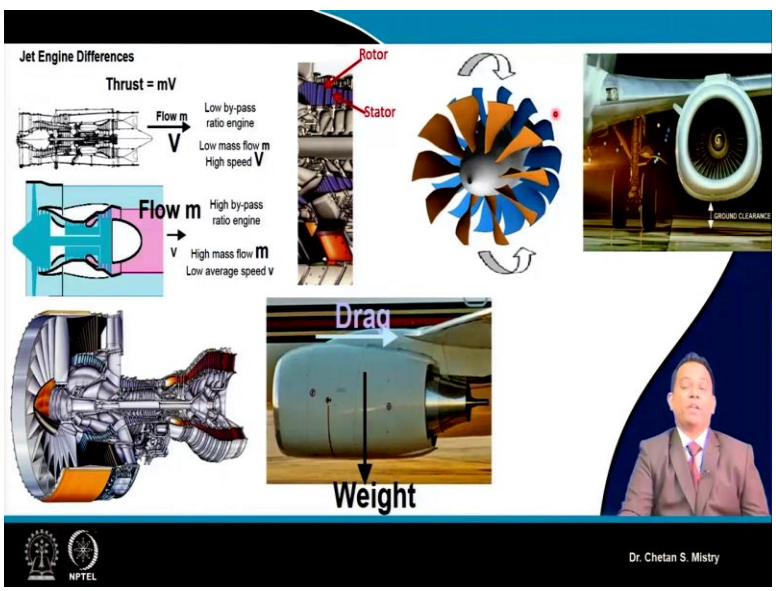

So, here if you look at, this is what is our development. We can say, earlier we were having our say turbo jet engines where my thrust requirement, that's what was been fulfilled by my mass flow rate into exhaust velocity, and if you recall, we were discussing that can be increased or the thrust can be increased by increasing either your mass flow rate or exhaust velocity.

Now, since my dimensions for turbo jet engine, that's what is fixed and that is the reason why increase of mass flow rate, that's what is a constraint. Next option that's what was with us, it is to increase the exhaust velocity, but when we are talking for increasing the exhaust velocity, my turbine entry temperature, that needs to be higher. And that's where the constraint, it has come with the type of material what we are using for the turbine.

Next, we have thought of having new kind of concept, that's what is say high bypass ratio or low bypass ratio engine. If you are talking about commercial aircraft application, we are having high bypass ratio engine where it says around approximately 70% of your thrust, that's what will be generated by fan only, and remaining 30%, that's what will be by the core engine. We have discussed about what all are the advantages for say high bypass ratio engine and low bypass ratio engine.

So, we will not be discussing that again here but let us try to understand what is this what we are looking for the future. So, here in this case, this is what is our high bypass ratio engine. It says by increasing the diameter of my fan, since we are getting say 70% of thrust by using the fan, so idea will come, let us increase the diameter of this fan. What will happen? If we are increasing the diameter of our fan, then there may be chances that we will be having this ground clearance to be very low.

So, there may be chances when we are taking off or during landing, this engine will be touching to the ground and that's what will be giving the failure of your engine as well as aircraft. And that's where the constraint has come; so, you cannot increase the diameter of engine beyond certain range, okay. Now, one more thing is if you look at, this is what is our engine, there is nothing wrong with this engine, but you can understand that's what is having component that we say stator and rotor, that's what is making stage, okay.

So, here in this case, if we are looking at for LP compressor, for HP compressor, we will be having more number of stages in order to have higher total pressure rise, or we can say, higher overall pressure ratio. So, since we are expecting our thrust to be larger, that means we are looking for our overall pressure ratio also to be larger. That means we are looking for more number of stages.

When we say we are increasing the number of stages, that means we are increasing basically our weight of the engine. At the same time, we are increasing the length of our engine. What is happening? That's what is increasing our drag, and that is also constraint in sense of specific fuel consumption. So, for near future or say upcoming future, people, they are looking for some kind of alternatives in order to address this kind of issues along with the environmental constraint, that's what was imposed by regulatory body.

And that's what has given say idea or motivation to go with different kind of configuration; we can say, that's what is say contra rotating configuration. Here, in this case, you can realize these are the two rotors: one, that's what is rotating in clockwise direction, the other one, that will be rotating in counter clockwise direction. So, question will come, what happens? So, there are many advantages, there are many benefits, that's what we will be discussing in the initial class.

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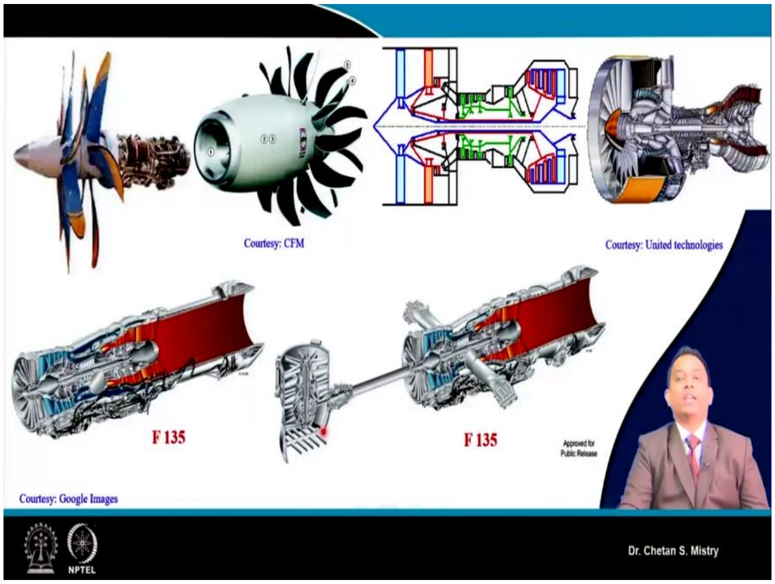

So, let us see. Suppose say this is what we are discussing about our high bypass ratio engine and as we discussed, people, they started working on the concept of contra rotating. So here, if you look at, this is what is a Russian engine that's what was connected or that's what was installed on Antonov. Here, we are having two propellers which are rotating in counter clockwise direction.

Now, these propellers which are rotating in counter clockwise direction, you can imagine when you are sitting in the aircraft and if you look at outside, if two rotors, that's what is rotating in open, it is a scary kind of situation. Same way, GE, they have started working earlier in 80s for development of say contra rotating un-ducted fans, and later on they have stopped that project, but still as on today they people, they are working on the development of un-ducted kind of configuration.

We are not interested for our course for un-ducted kind of configuration. We are more interested in ducted kind of configuration. So here, if you look at, this is what is one of the engine, you can see, they are having three spool configuration. So here if you look at, this is what is my HP spool, and on other side, blue color one, that's what is say…we can say, it is LP or you can one of the spools, and other spool that's what is say orange one.

So, this blue and orange you can understand that is nothing but that's what is giving us contra rotating kind of configuration, okay! So, here we will be having our main fan, that's what will be rotating in counter clockwise direction. And at the same time, our turbine also will be rotating in counter clockwise direction. So, we are having contra rotating fan and we are having contra rotating turbine, okay.

Now these are the two most recent engines. If you look at, this is what is representing F-135 engine that's what was developed by United Technologies Pratt & Whitney. And if we look carefully, all the compressor stages, they are say contra rotating; and turbines, they are also contra rotating. So, this engine, that's what has been fitted with fifth generation aircraft, what we say F-35. So, the technology that has already been proven in sense of adoption of contra rotating kind of configuration.

Now, this engine, that's what is fitted with the aircraft that's what is having VTOL kind of configuration, so it is having vertical takeoff and landing, and for that purpose they have fitted with fan configuration. That fan also is contra rotating kind of configuration, so you can see here. So, this is what is giving benefit in sense of say vertical takeoff and landing. So, technology in sense of development and use of contra rotating fan, that's what has been proven, and this engine, they are already been exist.

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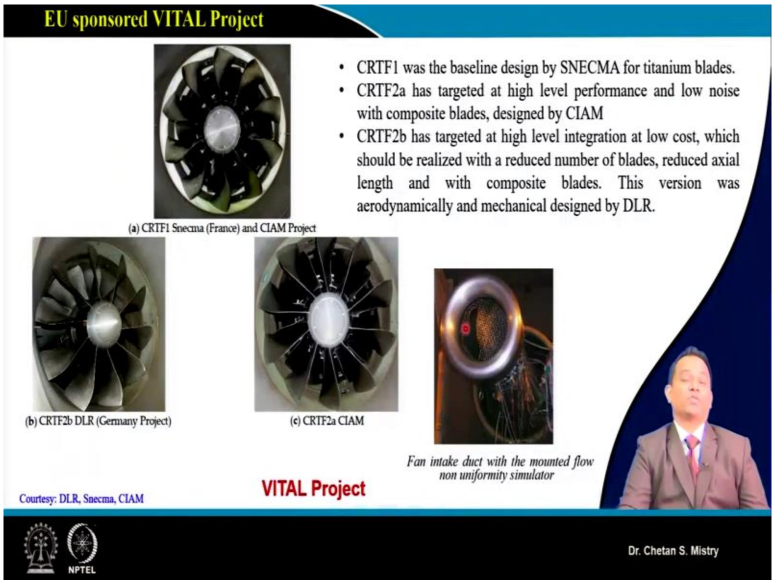

Now parallelly, in Europe, if you look at, there was a project that's what was initiated 10 years back, that's what is called VITAL Project. And for that VITAL Project, there are different organization which have been involved say, SNECMA, say…CIAM Lab, Russia, and DLR; they people, they have designed three different kind of configuration with different materials, with different aspects, okay.

So, these all we are looking for, they all are contra rotating kind of configuration, and they are been tested at CIAM Lab, Russia, okay. And here if you look at, this is what is say distortion screen, that's what is making artificial distortion. We will be discussing this. This is very important when we are talking about say application of this contra rotating.

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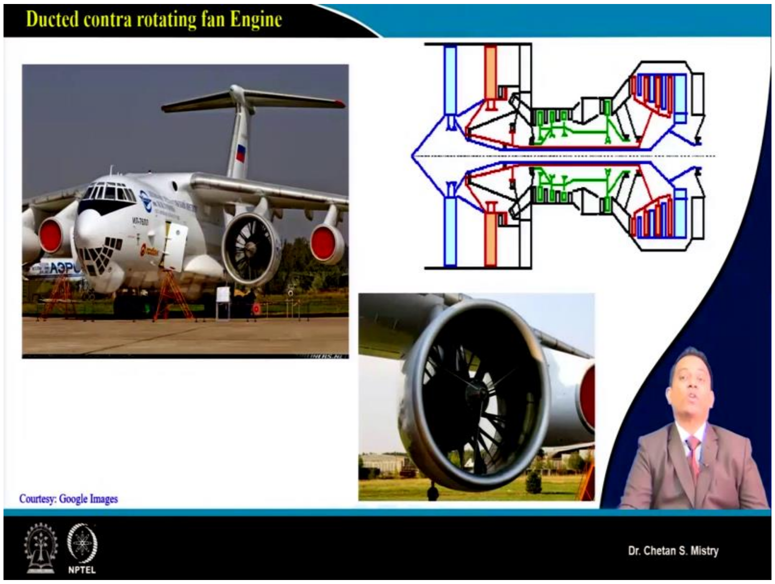

Now, this is what is already been developed engine, and that's what has been tested in Russia, that's what is fitted with this test aircraft. So, you can say, this is what is the progress for this contra rotating kind of configuration.

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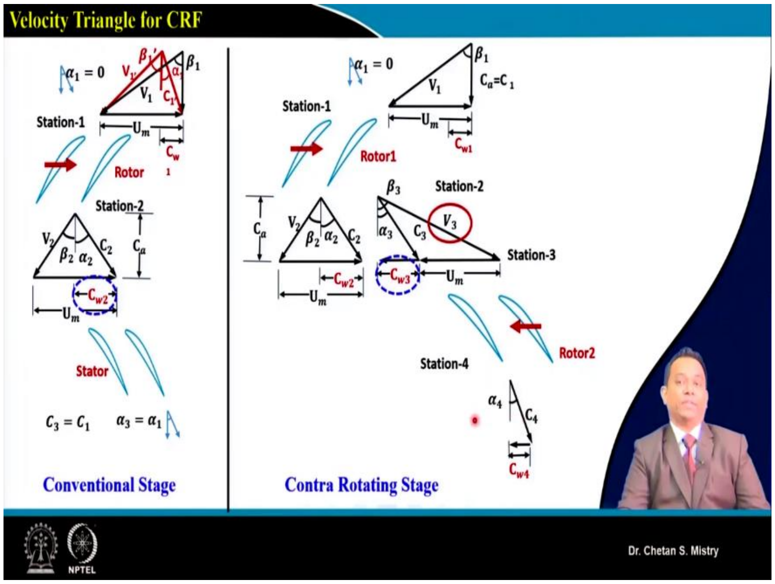

Now, the question will come what is there, what motivates people to go with say new kind of technology. So here if you look at, we will try to understand with our fundamentals what all we know. This is what is representing my velocity triangle for say conventional stage.

And if you look at carefully, suppose I can assume my flow, that's what is entering axially or it may be entering at some angle to my rotor, okay.

And my flow, that's what will be coming out from the rotor, that's what is representing this velocity triangle. What we realize? We are having say whirl component that's what will be coming out from the rotor. So, if you recall, when we have started discussing say this chapter for designs, that time we have discussed about different kind of configuration, only rotor, rotor-stator, stator-rotor, all those configurations, we have discussed.

That time also we have discussed about this aspect. What we say? This is what is my whirl component, that's will be coming out and that's what we are straightening by using this stator, okay. Now, in line to what all we have discussed here, say we are having two rotors, one that's what is rotating in this direction, you can say in the clockwise direction, and other rotor that's what is rotating in counter clockwise direction.

So, my entry velocity triangle, we can say, it is similar to what we have seen here. Now at the exit of my rotor, rotor-1, I will be having this as my velocity triangle. Now, here in this case, we are not having any stator, okay. We are having rotor and immediately I will be having second rotor, that's what is rotating in opposite direction.

What it is doing? You can understand, my flow that's what will be coming out from rotor-1 with some absolute velocity and flow angle α_2, same flow we can assume that's what is entering inside my rotor-2. Since it is rotating in opposite direction. So, let me put this direction of rotation, this is what is say my U, okay.

Now, what it will be doing? We know our velocity triangle that needs to be a closed velocity triangle. So, let me put this as say closed velocity triangle. Now, if we look at, this is what is say my whirl component that's what is coming out from my rotor-1. That's what is being sucked by my rotor-2, and that is the reason why here if you look at, this is what is giving me C_{w3}, and that's what is added component to my peripheral speed.

Here in this case, no. Here, if you look at, since my direction of rotation and my whirl component that's what is coming, they both are in same direction, so what basically it is doing? Here if you look at, that's what is giving me my relative velocity to be large at the entry of my rotor-2, okay. And we know this part. Suppose if you are looking at, say this is what is happening with my V_3.

And say this is what we say in sense of what is happening with my C_{w2}. Here this C_{w2}, we are not utilizing in sense of what we need to do. But at the same time, this C_{w2} and C_{w3}, they both are same, and in opposite direction, that's what is giving me my relative velocity at the rotor-2, it is entering at high relative velocity, okay. Now, this is what we can say my flow, that's what will be coming out at the exit.

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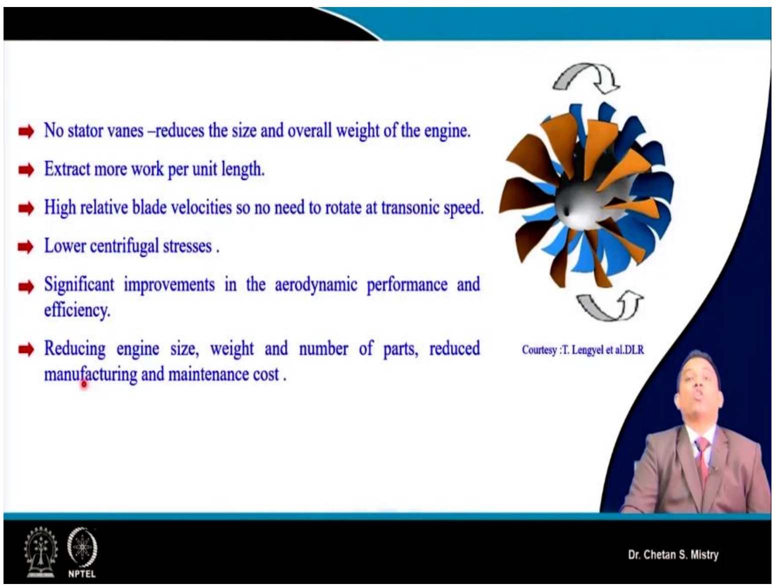

So, what we realize based on our understanding here, that's what is say, you know, we are having no stator. When we say there is no stator, that's what is will be reducing my size as well as overall weight of the engine, that's what is the promising feature, okay. Secondly, we can extract more amount of work, okay, per unit length. So, you can understand, say…since we are having less number of stages for contra rotating configuration for the same length as your actual engine has, we are configuring that's what is giving me higher amount of work that's what can be extracted.

We are having higher operating relative velocity. We have realized at the entry of my rotor-2 my relative velocity seems to be higher. What it says? This is the reason why there is no need for us to rotate our rotor at high speed. There is no need to rotate at transonic speeds, and that's what is lowering the centrifugal stresses, okay. And significant improvement, that’s what we are getting in sense of aerodynamic performance, and efficiency, as well as operating range also.

So, in overall if you look at, by incorporating or adopting this contra rotating concept, we are able to reduce the size, weight, number of components and we are able to reduce the manufacturing and maintenance cost, okay. And that’s what is attracting the use of this contra rotating concept for the engines, okay. And whole lot of research and development activities, that’s what is going on for application of this contra rotating fan for say aero engines.

This has other applications also. Many industrial fans, people, they started using this concept of contra rotating. Many ventilation fans where size is a constrained, they people, they are opting with this contra rotating configuration. For future electric propulsion system, for that also, people, they started opting with this kind of configuration. So, there are many ongoing applications, and there are many future applications based on what all benefits we are getting by incorporating this concept.

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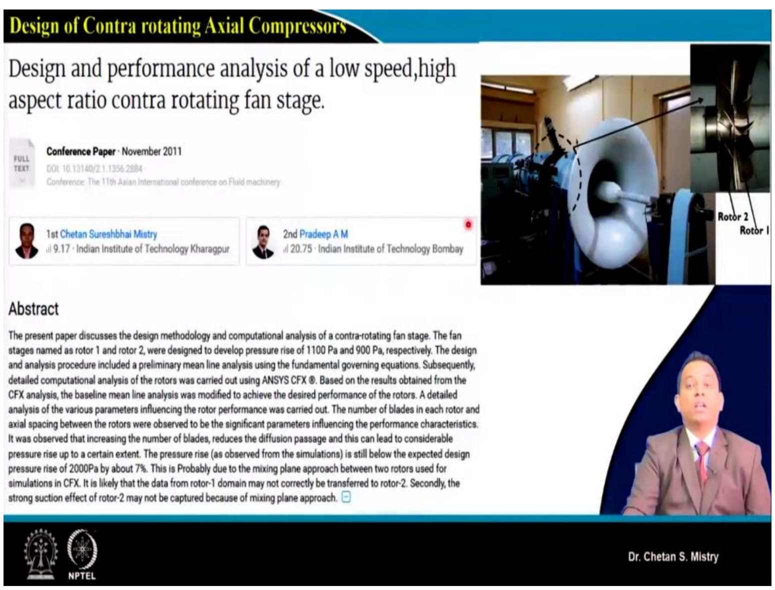

Now, in order to realize that part, during my doctoral study, we have worked on design and development of contra rotating fan stage at IIT, Bombay. So, this is what is my experimental facility. You can say, we are having two rotors, they both are rotating in opposite direction, so design of this contra rotating fan, that’s what is very challenging in sense because there is no open source discussion that's what is available for design, okay. So now, this work, that's what is available online. If you are interested, you can go through that part. That's what will give the confidence and idea how do we build our contra rotating fan configuration.

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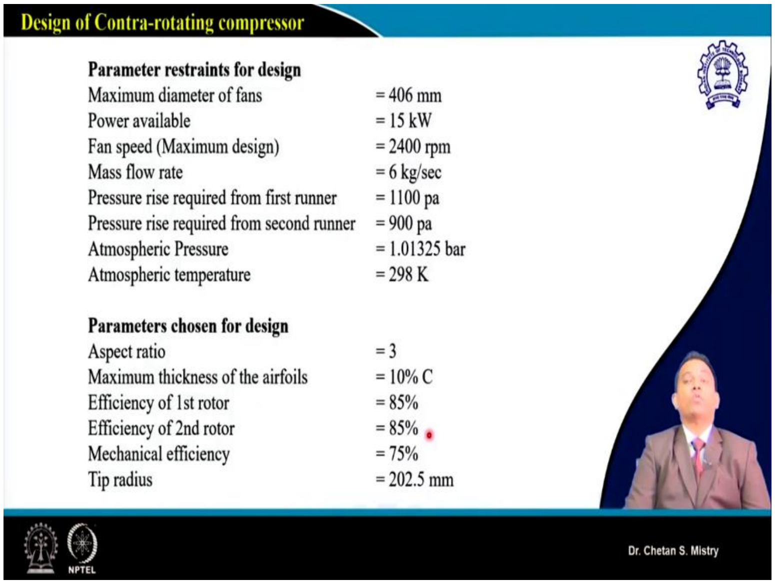

So, what all parameters we have selected for this, is we are having some restraints for say our design. So maximum diameter of the fan, that's what is available, that is 406 mm, because at the entry, we are having our bell mouth. This bell mouth, that's what was available with the laboratory, and that's what is having inner diameter of 406 mm.

And that is the reason why this is what is say 406 mm, the motor, that's what are available, they are in the range of say 15 kW, rotational speed is 2400 rpm, mass flow rate that's what we have taken as, or assumed as 6 kg/s. Now here, in this case, there is one important aspect, that's what we need to realize, what kind of pressure rise we are expecting.

Because, we are having two different rotors, okay. So, for our design, we have taken the total pressure rise for the stage by both the rotor, that's what is say 2000 Pa. And based on experience, and based on the confidence level, we have taken, we have assumed our rotor-1 to be highly loaded. And we have taken that as say 1100 Pa for rotor-1 and we are expecting total pressure rise for rotor-2, that's what is say 900 Pa.

We will see what is the meaning of higher loading of rotor-1 and these are say some of the parameter which have been chosen. So, for our design, we have taken our aspect ratio to be 3, because we are discussing, we are talking about the design of fan. This same concept, we can say we can opt for design of our say HP compressor also, where we will be going with aspect ratio to be slightly on the lower side, maybe aspect ratio of 1 or 1.2. But for our configuration, we have taken aspect ratio to be 3.

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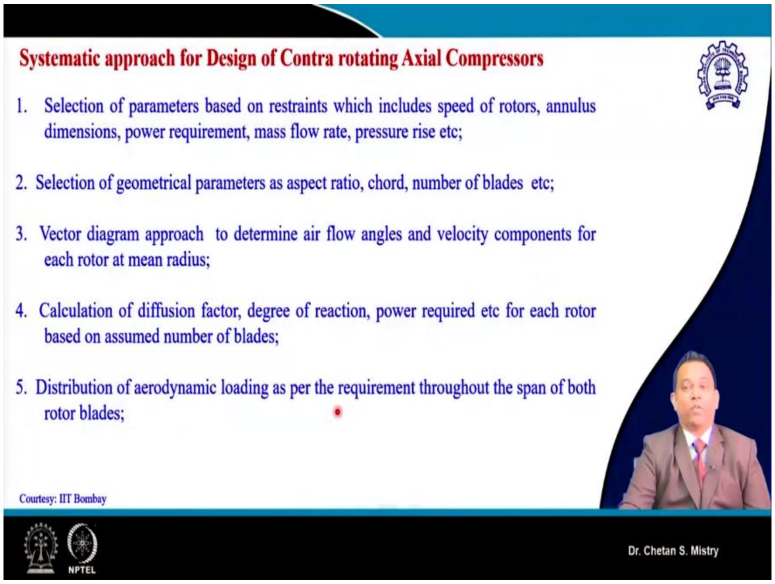

Now, these are the systematic approaches which are being opted for the design. So, we can say, based on what all we have restraints, we have opted for say speed, we have gone with the annulus dimension, power requirement, mass flow rate and pressure rise. And we will see what all are the global parameters for the design, and what all we have opted for. So, selection of geometrical parameters like aspect ratio, chord, number of blade, that's what has been initially assumed.

Then what all we have learned for say design of axial flow compressor, we have gone with say velocity triangle, calculation of different velocity components, then we have calculated our performance parameters in sense of design say diffusion factor, degree of reaction, power requirement. Based on that, we have finalized with some of the parameters, okay. Very important thing, that's what is say aerodynamic loading, that's what is required throughout the span, okay, for both the rotors.

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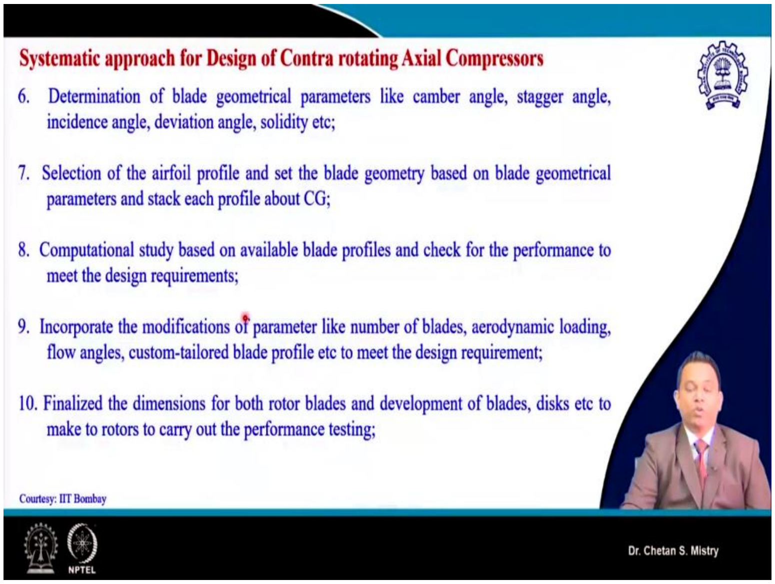

Then, based on all parameters, we have done our design, then we have calculated our flow angles what we have discussed about, incidence angle, deviation angle, camber angle, stagger angle. Based on similar approach what we have opted for, we have also made our blades. We have stacked them, both the rotor blades about the CG.

Once, that's what is ready with us, we have gone with say computational study. And based on that modifications, they have been done in order to achieve expected performance. These modifications, like maybe number of blades, aerodynamic loading, flow angles, custom tailor profile, so all these things that's what has been opted for.

And the paper what I am putting, that's what is having all these discussions available in open source. You can go with that part. And based on doing this design, we made our rotor. So, let me show you. These are our rotors, based on what all calculation we have done, okay.

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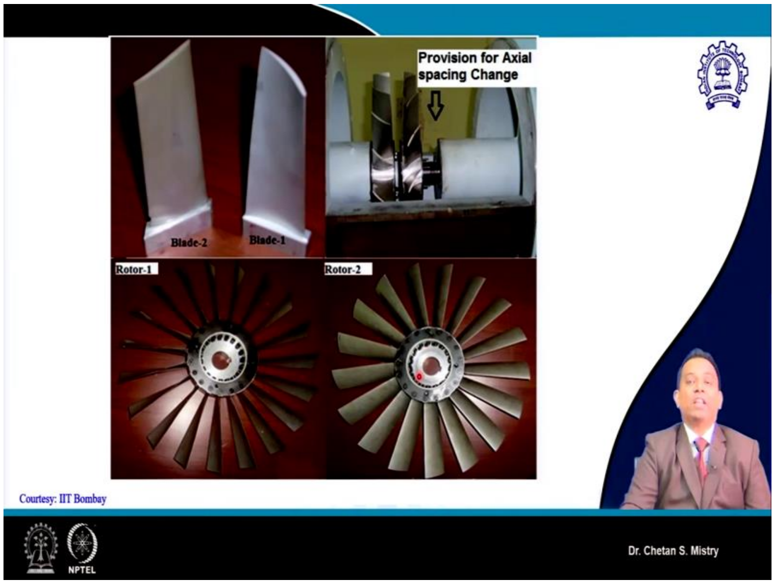

The purpose here to showcase is what all we are doing in sense of design, that's what we are making also. So, that's what will give more confidence in sense of design and development activity, at the same time, research activities.

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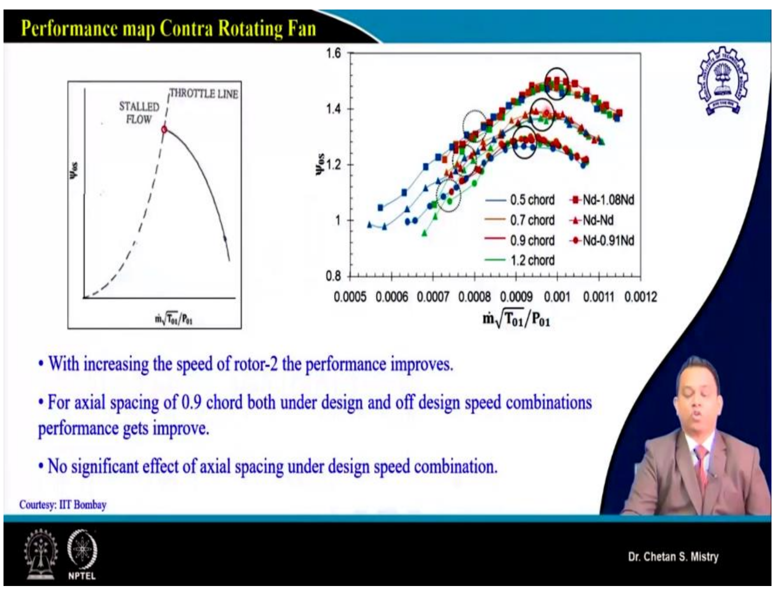

Now, conventionally, let me discuss about what we say in sense of operating range and performance. So, if we look at here, this is what is representation of say performance map for say our stage. So, we will be having, with decrease of mass flow rate, we will be having rise of pressure, and at one point, we will be having stall.

Now, this is what is the performance map what we have achieved based on what experimental facility we have developed. Here, it is very interesting to observe we are having two points, say…this is what is say partial stall and this is what is representing full stall. So, if we look at carefully, by incorporating this contra rotating kind of configuration, we are able to increase our operating range.

Since our target, that’s what was with change of different speed combination, what is the change in the performance, that’s what was one of the parametric studies for us. What need to be the axial spacing between two rotors? If you will be putting too nearby, what will happen, if you are putting too far, what will happen, and what need to be the optimized one.

So, it says for our kind of configuration it is roughly coming say 90% of our chord. And, here if you look at, with increasing the rotational speed of rotor-2, we are able to achieve high pressure rise. But at the same time, we have to compromise somewhere in sense of our say operating range. And this, I say, partial stall and this is what is representing say full stall configuration that will be more clear if you will be putting say individual performance of the rotor.

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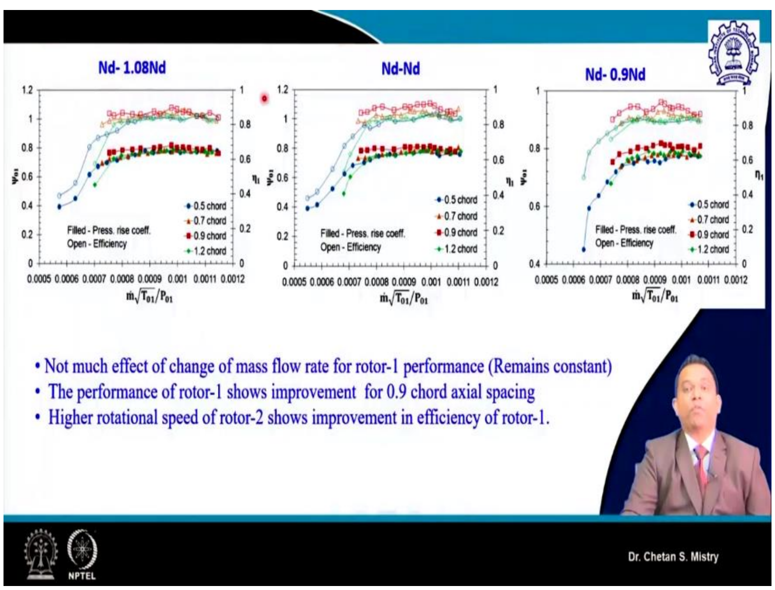

So, these are the performance for my both the rotors at different speed configuration. Here, if you look at, this is what is with design speed, both the rotors are rotating at design speed, here in this case, my second rotor, that's what is rotating at the high speed, and this is what is representing my second rotor when it is rotating at the low speed.

And if you look at carefully, this filled one, that's what is representing my total pressure rise coefficient. And if you observe carefully, it says for wide range of my mass flow rate, my rotor-1 is not getting stalled. That's what is the benefit of what we say, in sense of higher aerodynamic loading of rotor-1. So, for all the three configurations when you are checking with, it says my performance of rotor-1, it is not getting changed with the change of mass flow rate, okay.

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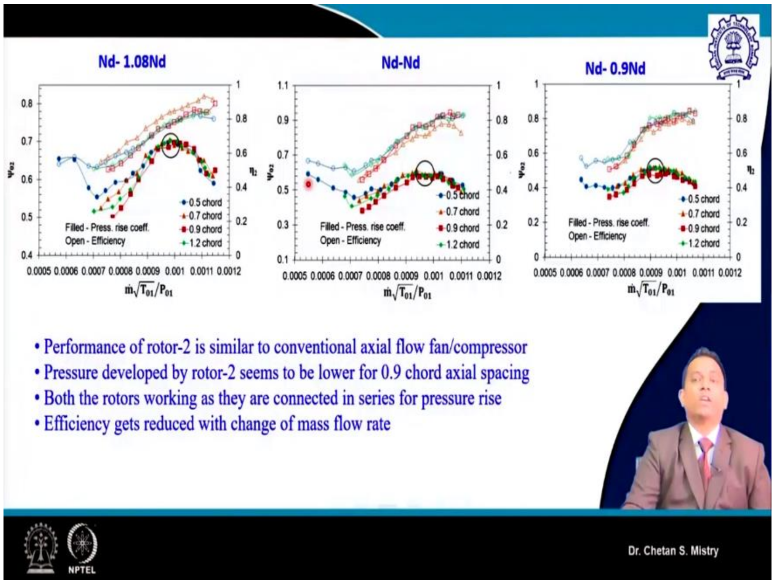

Now, if we look at, if we compare, what is happening with the rotor-2, it says my rotor-2 that's what is acting in line to what conventional rotor that's what is working with. So, with decrease of mass flow rate, it will be having say, this is what is my stall of rotor-2. That is the reason I have discussed that as say partial stall condition. You can see, by incorporating these two rotors, that too which are rotating in opposite direction, that's what is giving wider operating range. That's what is a benefit.

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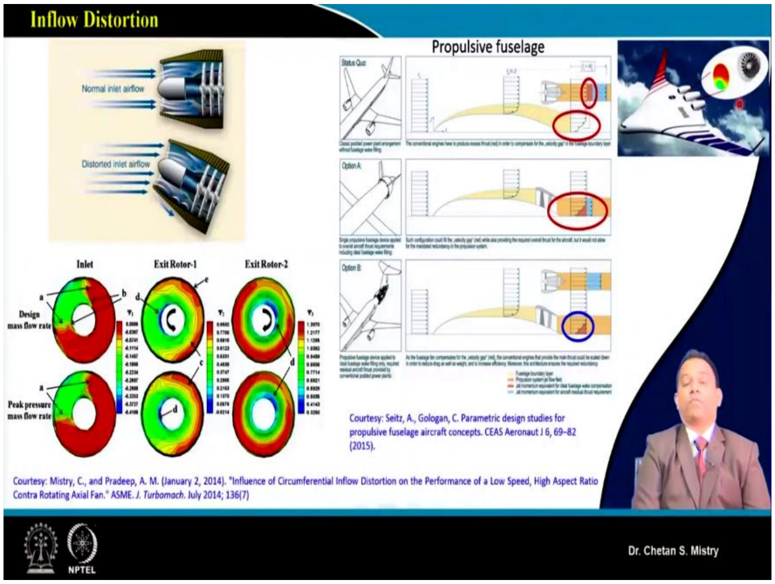

Now, one more configuration, one more study what was conducted, that's what is in sense of what is the effect of inflow distortion. So, conventionally if you look at, when my aircraft that's what is flying at the cruise condition, my flow, that's what is going clean or parallel to my engine axis, okay. When we are taking off or landing, that time, it may be possible that in some of the region my air, that's what will not go as per our expectation, okay.

And we are having different kind of inflow distortion. These inflow distortions are because of change of temperature, change of total pressure, change of velocity, because of presence of wake or maybe climatic change. All these, that's what will be bringing the change or say that's what is called say inflow distortion. So, when we are sitting in aircraft, it is used to say turbulence. So, that turbulence is nothing but, in language for aero engine people used to say, inflow distortion, okay.

And that's what will be led to reduce or deteriorate the performance. Sometimes, if it is of extreme, it may be possible that, that will lead to failure of the engine, okay. And if your engine is failed, your aircraft, that's what has failed; that's the reason this is what is a very serious matter. Now, in order to understand what is happening with inflow distortion on contra rotating configuration, we have generated artificial distortion here.

So, you can see, we have taken 90° sector at the entry of my rotor-1. And this are the measurements using seven hole probe before rotor-1. And you can see, this is what is the propagation of distortion under two different configurations, okay. You can say this is what is my design mass flow rate and this is what is my peak pressure mass flow rate configuration.

Now, very interestingly, at the exit of my rotor-1 or between two rotors, we have done the measurement of total pressure. So, if you look at here, this is what is representing what is happening with my total pressure at the exit of my rotor-1. And if you look at carefully, we can say this effect, that’s what is getting rotated in the direction of my rotor-1. And, you know, you are getting nearly uniform kind of total pressure distribution.

So, that’s what is kind of rotation of my distortion. Now, let me tell you when we are discussing about the stage, conventional stage, where we are having rotor and stator, what will happen? What all that’s what is coming out from my rotor, that’s what will be striking on the stator. Here in this case, because of rotation, we are having this to be moving in say direction of rotation of my rotor-1.

At the exit of rotor-2, if we consider, since this is what is rotating in opposite direction, we will see the effect of distortion that’s what is going to reduce, or we can say it is getting nullified at the exit of rotor-2. And that’s what is a need what we are looking for. The effect of inflow distortion that need to be minimized, okay, and that’s what we are getting by incorporating this contra rotating kind of configuration. So, this is also one of the benefits, okay.

Now, for future engines, people, they started talking about propulsive fuselage, where we are having our flow that’s what is entering inside the engine with some kind of inflow distortion. Here, if you look at, this is what is a future concept aircraft in which the engines are putted in your fuselage, okay.

The reason is, in order to reduce the noise, and in order to take the benefit in sense of installation and to get the wider space, okay, so this is what is wide body aircraft. Now the challenge that’s what is happening is, I will be having my growth of boundary layer from this front towards the rear side.

So, by the time my compressor that will be facing the flow, it will be having this kind of total pressure distribution. So, what will happen? This is what will be striking on my fan. Suppose say, we are using high bypass ratio engine or low bypass ratio engine, and that's what will lead to deteriorate the performance.

Now, the University of Cambridge and MIT, they people, they are working on development of such kind of configuration where they can minimize this inflow distortion, okay. So, these all are the benefits in sense of contra rotating fan configuration. So, that is the reason we feel, this concept or this design that need to be discussed, that need to be incorporated in the course and we will be discussing about this design, okay.

So, in next lecture, we will start discussing how do we design of contra rotating fan. At this moment, we are targeting low speed configuration. So, with this, if you are interested, you can collect the material. There are a lot of literature that is available from DLR, that's what is available from SNECMA, many literature they are available from CIAM, even from say India and China also.

So, lot of work, lot of research that's what is going on in sense of opting for contra rotating fan concept or contra rotating compressor concept for the engine. So here, we are stopping with. Thank you very much for your kind attention! We will be started discussing about the design from the next lecture.