Aerodynamic Design of Axial Flow Compressors and Fans
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Lecture 42
Design Low Speed Compressor (Contd.)

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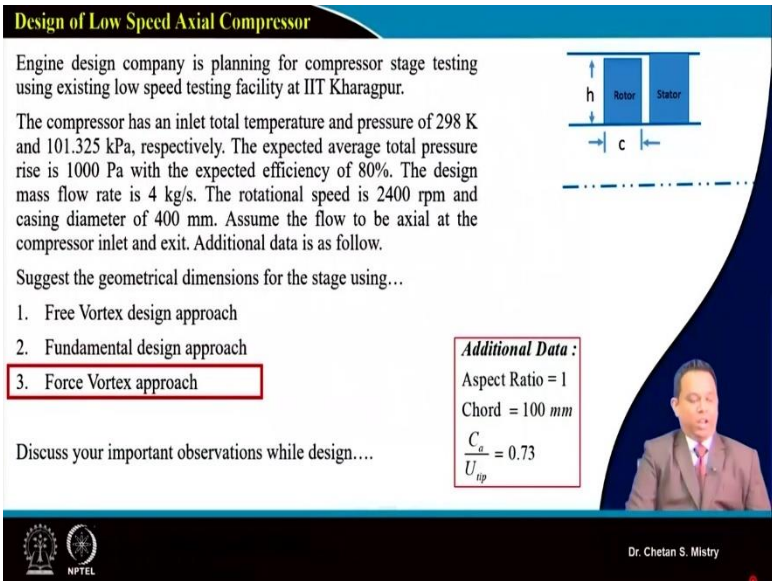

Hello, and welcome to lecture 42. We, are discussing about the design of low speed axial flow compressor. In last session, we have discussed about different design approaches. So, for this numerical we have solved by using approaches called say free vortex concept, we have used fundamental approach. Now, today we will be discussing about the force vortex concept.

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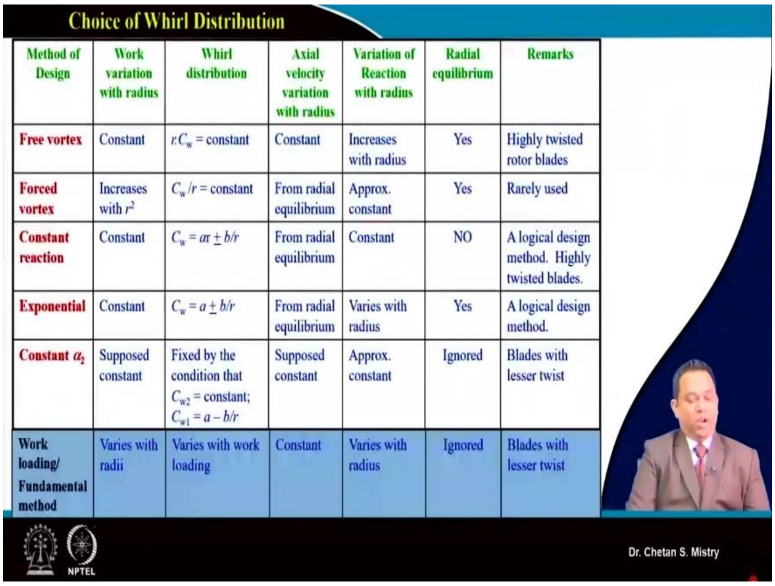
Choice of Whirl Distribution

Method of Design	Work variation with radius	Whirl distribution	Axial velocity variation with radius	Variation of Reaction with radius	Radial equilibrium	Remarks
Free vortex	Constant	$r.C_w$ = constant	Constant	Increases with radius	Yes	Highly twisted rotor blades
Forced vortex	Increases with r^2	C_w/r = constant	From radial equilibrium	Approx. constant	Yes	Rarely used
Constant reaction	Constant	$C_w = ar \pm b/r$	From radial equilibrium	Constant	NO	A logical design method. Highly twisted blades.
Exponential	Constant	$C_w = a \pm b/r$	From radial equilibrium	Varies with radius	Yes	A logical design method.
Constant α_2	Supposed constant	Fixed by the condition that C_{w2} = constant; $C_{w1} = a - b/r$	Supposed constant	Approx. constant	Ignored	Blades with lesser twist
Work loading/ Fundamental method	Varies with radii	Varies with work loading	Constant	Varies with radius	Ignored	Blades with lesser twist

Now, this is what is a table that's what we have made during our week 3. And, if you realize there are different methods which are available for design of axial flow compressors; out of which for this particular numerical we have opted with the free vortex design and we have opted using say work loading or our fundamental method. Now, today's lecture we will be focusing on force vortex concept. So, for force vortex, we can say our work, that's what we will be varying with r^2, our distribution for whirl that's what will be $\frac{C_w}{r} = constant$; we will be calculating our axial velocity based on say…our radial equilibrium equation.

Most important, how my degree of reaction, that's what we will be varying, that's what we need to check with. And this is the method, that's what is following our radial equilibrium. And, mostly this method, it is rarely been used; but still in order to understand different approaches, it is preferred to go with this also. So, you can understand like, we are solving the same numerical using different methods, that's what will be giving us fundamental idea how do we proceed with.

So, it will take many hours if we will be solving same numerical by using these seven methods. And that's what will not make much sense. And that is the reason why we have selected these three; because that's what is most widely been used and why it is not been used that is also we need to understand, okay. So, let us move with our next method, that's what is say force vortex method.

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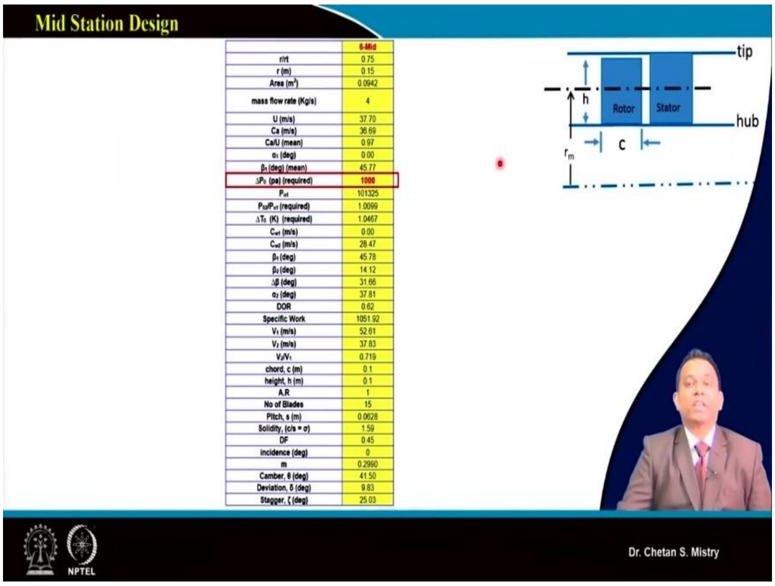

Now, here in this case, we know when we are designing our low speed axial flow compressor, for that we are doing all our initial calculation at the mid station. So, here if you look at, this is what is my mid station and that calculation…that excel sheet, that's what remains same for free vortex, for fundamental method as well as for force vortex better. So, my mean line calculation, that's what will be remained same as we have done for past two methods.

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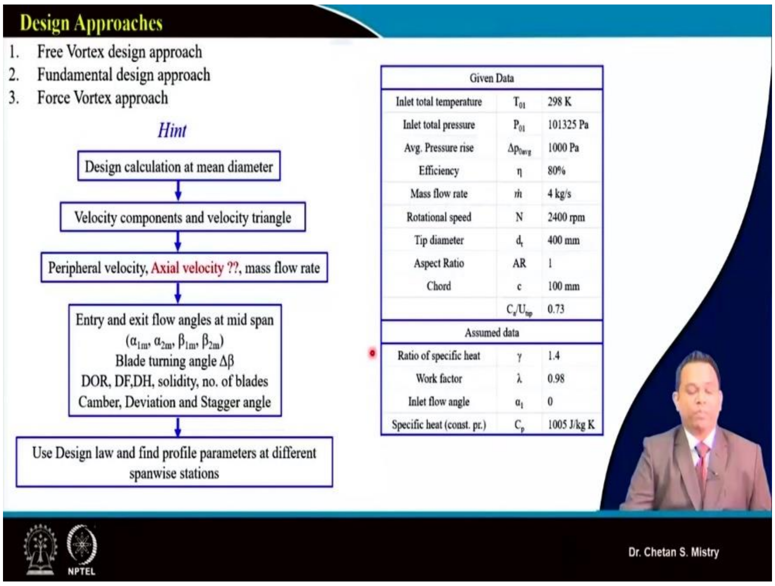

Now, when we say, we want to do design for say…force vortex concept, then we need to realize how do we proceed with. So, similar to what all we have discussed for earlier two methods, we will be calculating our different velocity components or velocity triangle will be checking with different velocity components; and as we know here in this case for force vortex concept, my axial velocity that will not remain constant; that means we need to do the calculation for that, okay. So, at entry and at the exit, we will be calculating different flow parameters, we will be calculating different say parameters called degree of reaction, diffusion factor, De Haller's factor, we will be calculating different flow angles at a particular station initially and then after we will be applying our design law for other stations, okay. So, let us see how do we proceed with.

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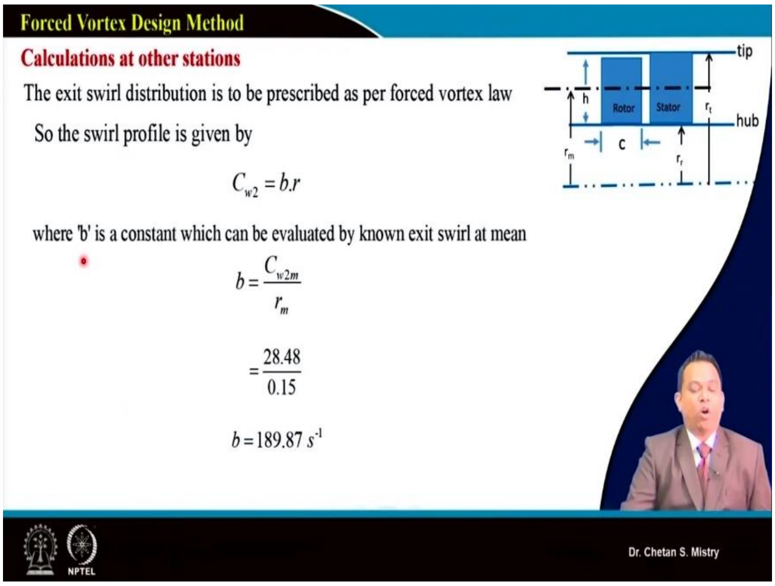

So, in order to do the calculation at different stations, say here in this case, it is given my entry is axial that means my C_{w1} or my whirl component at the entry it is 0, okay. Now, in order to solve this design or in order to do design, we will be assuming my whirl component at the exit that's what is following $b \cdot r$, that is $C_{w2} = b \cdot r$, okay. Since at mid station we know what is our C_{w2}, we know what is our radius, if we will be putting my C_{w2} at the mid station is 28.48, and my mid radius is 0.15, that's what will be giving me my constant b it is say 189.87 s^{-1}. So, we can say, now we know what is our constant.

$$C_{w2} = b \cdot r$$

$$b = \frac{C_{w2m}}{r_m}$$

$$= \frac{28.48}{0.15}$$

$$\therefore b = 189.87\ s^{-1}$$

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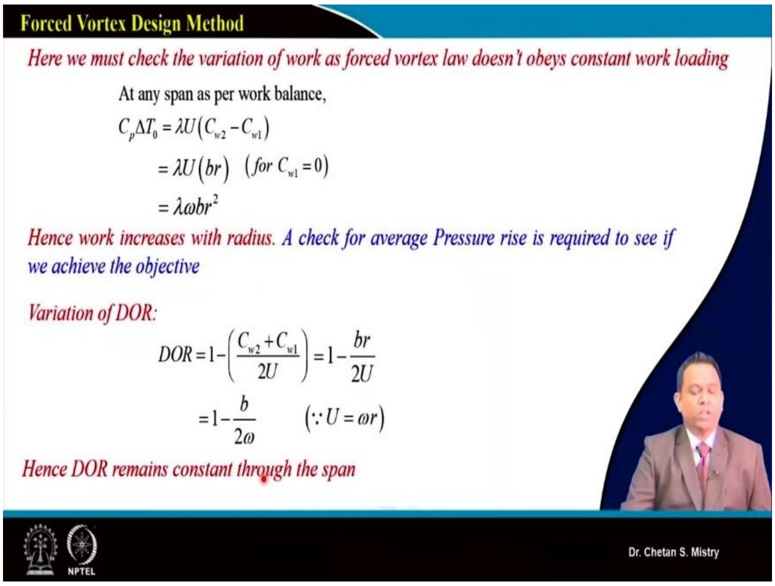

Now, this method we need to check the variation of work as force vortex, that's what is not following constant work loading, okay. So, what we can write down from our fundamental approach, we can say my thermodynamic work and aerodynamic work they both are same. Here in this case, what we know C_{w1}, that's what is equal to 0 and my C_{w2}, that's what we are putting say b into r.

$$At\ any\ span\ as\ per\ work\ balance,$$

$$C_p\Delta T_0 = \lambda U(C_{w2} - C_{w1})$$

$$= \lambda U(b \cdot r) \qquad (\because C_{w1} = 0, C_{w2} = b \cdot r)$$

$$= \lambda\omega br^2$$

So, you can say my work, that's what is varying with say r^2, okay. Now, the work, that's what is varying with the radius are checked for average pressure is required, if we are achieving our objective or not, we will see how do we proceed with. Now, important parameter, that's what is called say degree of reaction.

So, if you are putting this degree of reaction, my $C_{w1} = 0$ and $C_{w2} = b \cdot r$, that's what is saying my degree of reaction is given by $1 - b/2\omega$, ω is my angular speed.

$$Variation\ of\ DOR:$$

$$DOR = 1 - \left(\frac{C_{w2} + C_{w1}}{2U}\right) = 1 - \frac{b \cdot r}{2U}$$

$$\therefore DOR = 1 - \frac{b}{2\omega} \quad (\because U = \omega r)$$

So, we can say, my degree of reaction, that's what is independent of radius. Let me tell you here, we have assumed our force vortex by taking $C_w = b \cdot r$. So, if you recall, when we were discussing different approaches that time, we have discussed about arbitrary selection of whirl component. If that kind of configuration we are having, this degree of reaction, maybe having some different numbers, okay.

So, we need to check carefully for this kind of configuration. For say, $C_{w2} = b \cdot r$, we say our degree of reaction, that's what is independent of radius that means that's what remains constant, okay.

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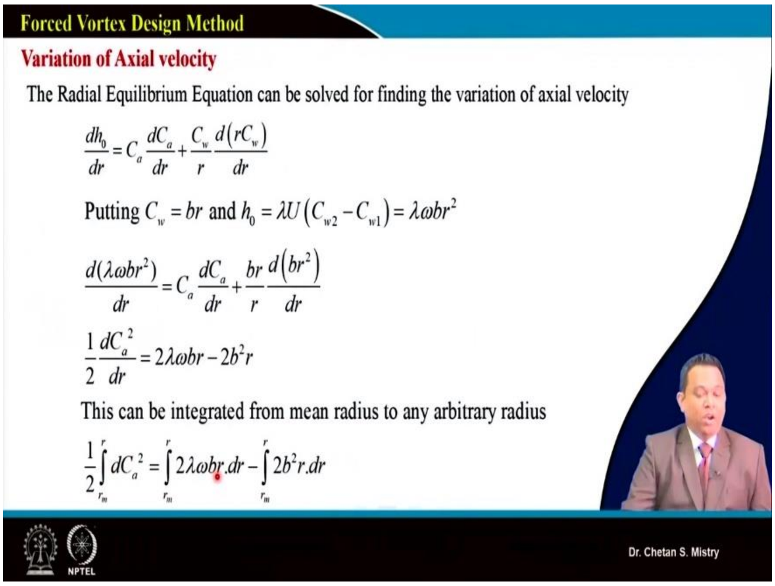

Now, what we realize is we do not know what is our axial velocity, because we know in order to satisfy the radial equilibrium, we need to have total enthalpy at say…throughout my radius or my work distribution, that's what will be remains constant. Second condition, that's what is my axial velocity, that's what is remains constant throughout my span and third, that's what is $C_{w2} \cdot r = constant$. If we are satisfying these three conditions, we can say, our radial equilibrium it is satisfied and then we have discussed maybe one of the parameter if you will be putting as a constant, other parameters can be calculated by using this radial equilibrium equation.

So, that's what we are doing here. So, this is what is my fundamental equation; it says

$$\frac{dh_0}{dr} = C_a \frac{dC_a}{dr} + \frac{C_w}{r}\frac{d(rC_w)}{dr}$$

Now, here in this case, what we know, my h_0 that is nothing but it is say $h_0 = \lambda\omega b r^2$, that's what we have calculated earlier.

$$Putting\ C_w = b \cdot r\ and\ h_0 = \lambda U(C_{w2} - C_{w1}) = \lambda\omega b r^2$$

Same way, my C_w we are putting that's what is say $b \cdot r$, okay. If you are putting this in this equation, it says we will be getting the formulation in the form of different radiuses, okay.

$$\frac{d(\lambda\omega b r^2)}{dr} = C_a \frac{dC_a}{dr} + \frac{br}{r}\frac{d(br^2)}{dr}$$

Now, this is what it says in sense of my $\frac{dC_a}{dr}$, that's what is equal to say

$$\frac{1}{2}\frac{dC_a^2}{dr} = 2\lambda\omega b r - 2b^2 r$$

Now, in order to do the calculation for the variation of axial velocity, we will be doing the integration from some location, say our known location, that's what is say r_m to any radius r. So, we can write down this equation in the form of integral form, okay.

$$This\ can\ be\ integrated\ from\ mean\ radius\ to\ any\ arbitrary\ radius$$

$$\frac{1}{2}\int_{r_m}^{r} dC_a^2 = \int_{r_m}^{r} 2\lambda\omega b r \cdot dr - \int_{r_m}^{r} 2b^2 r \cdot dr$$

So, this is what is nothing but this is what is giving me integral form.

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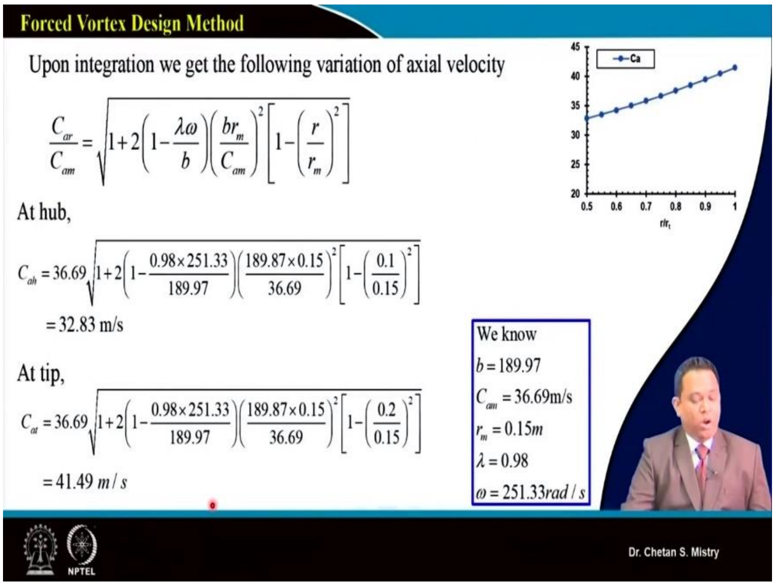

Now, if we are solving that, we will be getting say ratio of my axial velocity at any radius divided by my axial velocity at the mid station, that's what is given by this formula.

$$Uppon\ integration\ \ we\ get\ the\ following\ variation\ of\ axial\ velocity$$

$$\frac{C_{ar}}{C_{am}} = \sqrt{1 + 2\left(1 - \frac{\lambda\omega}{b}\right)\left(\frac{br_m}{C_{am}}\right)^2\left[1 - \left(\frac{r}{r_m}\right)^2\right]}$$

So, again, you can check with the module 3, where we have discussed about different design methodology. In that also we have discussed how do we calculate our axial velocity, that's what we will be giving you the idea.

So, now here in this case, we understand, say…my axial velocity at particular station, that's what is varying by this formula. So, let us calculate at say hub station. So, we can say at hub, we will be putting this number. It says at hub, my axial velocity is coming 32.83. We can understand at mid station we are having our axial velocity, that's what is 36.69, okay.

$At\ hub,$

$$C_{ah} = 36.69\sqrt{1 + 2\left(1 - \frac{0.98 \times 251.33}{189.97}\right)\left(189.87 \times \frac{0.15}{36.69}\right)^2\left[1 - \left(\frac{0.1}{0.15}\right)^2\right]}$$

$$\therefore C_{ah} = 32.83\ m/s$$

Now, what is happening at the tip? So, if you are putting these numbers, since we know what is our b, what is our axial velocity at the mid station, different radiuses, mid radius that's what will be giving me my axial velocity at the tip, that's what is 41.49 m/s.

$At\ tip,$

$$C_{at} = 36.69\sqrt{1 + 2\left(1 - \frac{0.98 \times 251.33}{189.97}\right)\left(189.87 \times \frac{0.15}{36.69}\right)^2\left[1 - \left(\frac{0.2}{0.15}\right)^2\right]}$$

$$\therefore C_{ah} = 41.49\ m/s$$

So, we can say near the hub, our axial velocity is lower; near the tip region, our axial velocity is coming to be higher.

Now, this is what is somewhat different compared to what all we have done for our fundamental method as well as what we have done for our free vortex method. For that we have assume our axial velocity to be constant, here in this case my axial velocity, that's what is varying.

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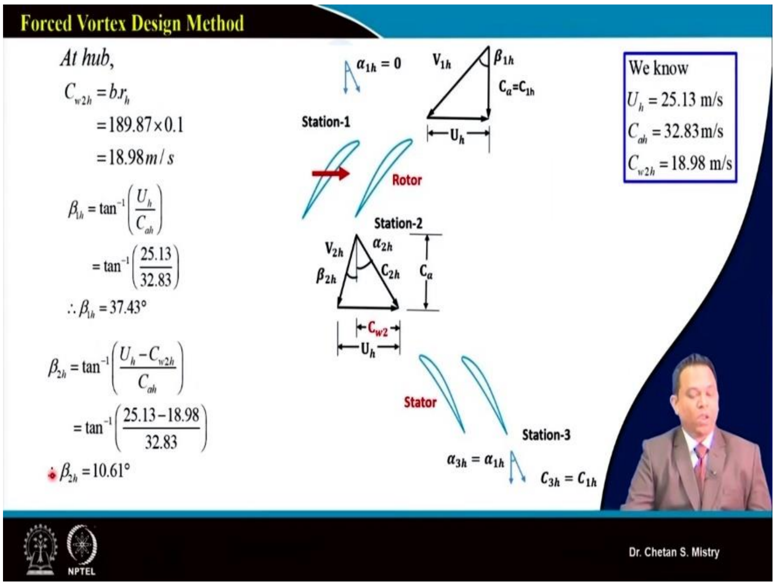

Now, we need to do our calculation since we are having our axial velocity to be different. So, we will do our calculation for different flow angles. So, if we are putting our velocity triangle; so, this is what is a triangle at the hub, we can say our C_{w2} it is nothing but $b \cdot r_h$, this b is our constant, that number we know it is 189.87 and hub radius is 0.1. So, that's what is giving 18.98 m/s.

$$At\ hub,$$

$$C_{w2h} = b \cdot r_h$$

$$= 189.87 \times 0.1$$

$$= 18.98\ m/s$$

We can calculate our β_1. Since, we know like my $\tan \beta$, that's what is given by U/C_{ah}. So, that's what it says β_1 it is coming 37.43, okay.

$$\beta_{1h} = \tan^{-1}\left(\frac{U_h}{C_{ah}}\right)$$

$$= tam^{-1}\left(\frac{25.13}{32.83}\right)$$

$$\therefore \beta_{1h} = 37.43°$$

Same way, at the exit also we can do our calculation for β_{2h} it is

$$\beta_{2h} = \tan^{-1}\left(\frac{U_h - C_{w2h}}{C_{ah}}\right)$$

$$= \tan^{-1}\left(\frac{25.13 - 18.98}{32.83}\right)$$

$$\therefore \beta_{2h} = 10.61°$$

Be careful! when you are doing your calculation you must make a habit to write down what all data you know at particular station, okay. Here, our axial velocity, that's what is not constant, that axial velocity is reduced. So, it is 32.83. So, do this calculation carefully. It says my β_2 at the hub it is coming 10.61, okay. So, we can say we know what is our relative flow angles, relative air angles.

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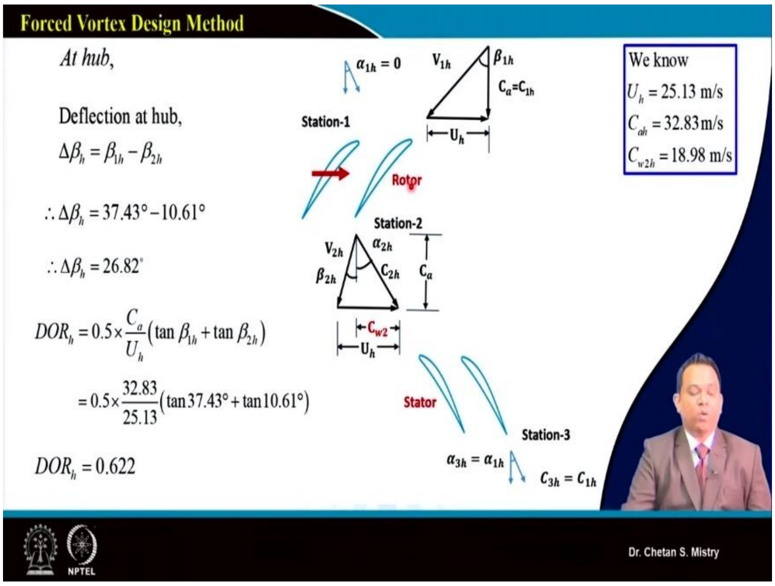

Now, at the hub we can calculate what is our $\Delta\beta$ since my β_1 and β_2 they are known to be. So, we can say $\Delta\beta$ at the hub, it is coming 26.82; just look at this number compared to what all methods we have solve where $\Delta\beta$ was coming to be different.

$$At\ hub,$$

$$Deflection\ at\ hub,$$

$$\Delta\beta_h = \beta_{1h} - \beta_{2h}$$

$$\therefore \Delta\beta_h = 37.43° - 10.61°$$

$$\therefore \Delta\beta_h = 26.82°$$

Here, you are looking this number to be different. Now, we can do our calculation for degree of reaction at the hub. This is what is a formula, since my C_a at hub it is known. So, we can do this calculation. It says my degree of reaction, that's what is coming 0.62, okay.

$$DOR_h = 0.5 \times \frac{C_a}{U_h}(\tan\beta_{1h} + \tan\beta_{2h})$$

$$= 0.5 \times \frac{32.83}{25.13}(\tan 37.43° + \tan 10.61°)$$

$$\therefore DOR_h = 0.622$$

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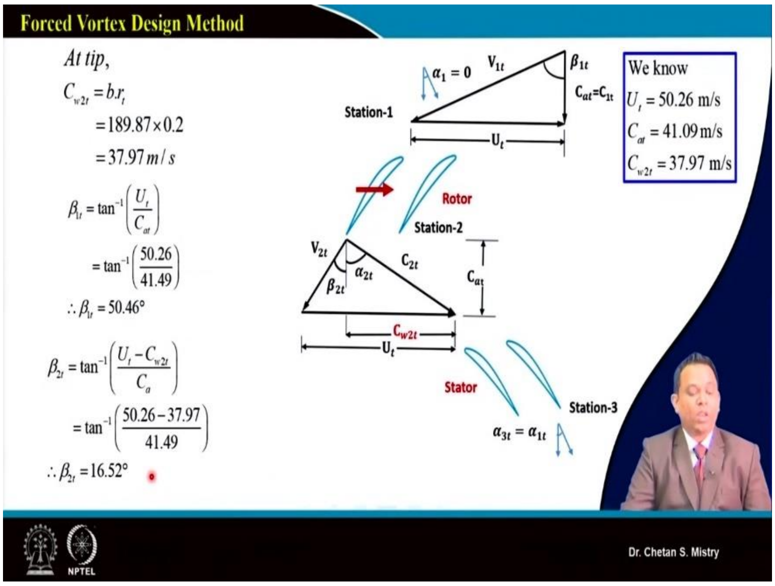

Now, we can do our calculation at say tip station in line two what we have done at the hub station. So, that's what is say $b \cdot r_t$, that's what we are putting here, okay. So, we can calculate our C_{w2}, we can calculate what is our β_1, what is our β_2 in line to what calculation we have done at say hub station as well as at tip station. This is what will be my velocity triangle, okay.

$$At\ tip,$$

$$C_{w2t} = b \cdot r_t$$

$$= 189.87 \times 0.2$$

$$= 37.97\ m/s$$

$$\beta_{1t} = \tan^{-1}\left(\frac{U_t}{C_{at}}\right)$$

$$= tam^{-1}\left(\frac{50.26}{41.49}\right)$$

$$\therefore \beta_{1t} = 51.46°$$

$$\beta_{2t} = \tan^{-1}\left(\frac{U_t - C_{w2t}}{C_{at}}\right)$$

$$= \tan^{-1}\left(\frac{50.26 - 37.97}{41.49}\right)$$

$$\therefore \beta_{2t} = 16.52°$$

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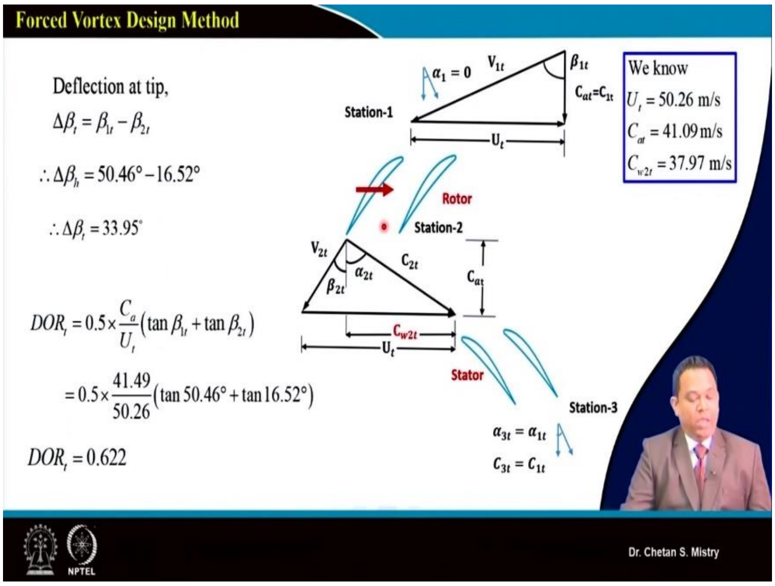

Now, based on this formulation, we can calculate what will be our $\Delta\beta$. So, you can say my $\Delta\beta$ near this tip region that's what is coming 33.95, okay.

$$At\ tip,$$

$$Deflection\ at\ tip,$$

$$\Delta\beta_t = \beta_{1t} - \beta_{2t}$$

$$\therefore \Delta\beta_t = 50.46° - 16.52°$$

$$\therefore \Delta\beta_t = 33.95°$$

$$DOR_t = 0.5 \times \frac{C_a}{U_t}(\tan\beta_{1t} + \tan\beta_{2t})$$

$$= 0.5 \times \frac{41.49}{50.26}(\tan 50.46° + \tan 16.52°)$$

$$\therefore DOR_t = 0.622$$

And, degree of reaction, that's what is coming 0.62. So, this degree of reaction what we are calculating, that's what is coming to be constant at hub, mid and tip station, okay.

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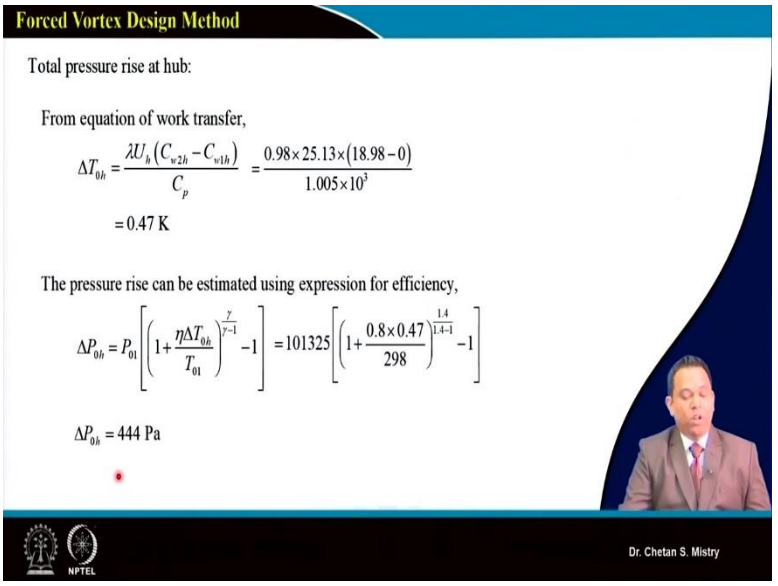

Now, next parameter, that's what is very important here in this method. So, we have seen our work, that's what is varying throughout my span, because that's what is changing with r^2. So, in order to take care of that, we need to calculate what will be my ΔT_0 at particular station, we need to check with what will be our ΔP_0, okay.

So, here in this case, we know from our fundamental equation, ΔT_0 at the hub, that's what is given by this formula, we are comparing our aerodynamic work and our thermodynamic work.

At hub,

$$\Delta T_{0h} = \frac{\lambda U_h (C_{w2h} - C_{w1h})}{C_p} = \frac{0.98 \times 25.13 \times (18.98 - 0)}{1.005 \times 10^3} = 0.47\ K$$

So, if you are putting this number it says my ΔT_0 at the hub is coming 0.47 K, okay. Now, from our understanding of say our efficiency, we can do our calculation what will be my ΔP_0 at the hub.

So, if you are putting this number, it says at hub, we are having our ΔP_0 to be 444 Pa.

$$\Delta P_{0h} = P_{01}\left[\left(1 + \frac{\eta \Delta T_{0h}}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} - 1\right] = 101325\left[\left(1 + \frac{0.8 \times 0.47}{298}\right)^{\frac{1.4}{1.4-1}} - 1\right]$$

$$\Delta P_{0h} = 444\ Pa$$

Now, look at and compare this with what all we have discussed up till now. For free vortex, what we have discussed we are not having any variation of h_0. If you look at for say our fundamental approach, where we are assuming this ΔP_0.

Now, for this force vortex method, applying force vortex concept, we are calculating what is our ΔP_0 at that particular station, okay. Now, similarly, we can do our calculation what is happening near the tip region. So, it says ΔT_0 at the tip, it is coming 1.86 K and my ΔP_0, that's what is coming 1783 Pa, okay. So, this is what is a cross check kind of thing, how my ΔP_0, that's what is varying along my span, okay.

$At\ tip,$

$$\Delta T_{0t} = \frac{\lambda U_t (C_{w2t} - C_{w1t})}{C_p} = \frac{0.98 \times 50.27 \times (37.96 - 0)}{1.005 \times 10^3} = 1.86\ K$$

$$\Delta P_{0t} = P_{01}\left[\left(1 + \frac{\eta \Delta T_{0t}}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} - 1\right] = 101325\left[\left(1 + \frac{0.8 \times 1.86}{298}\right)^{\frac{1.4}{1.4-1}} - 1\right]$$

$$\Delta P_{0t} = 1783\ Pa$$

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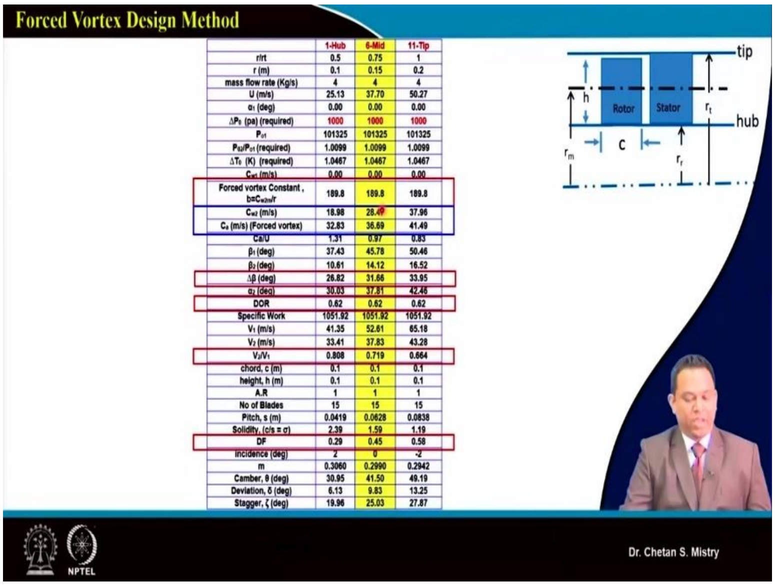

	1-Hub	6-Mid	11-Tip
r/rt	0.5	0.75	1
r (m)	0.1	0.15	0.2
mass flow rate (Kg/s)	4	4	4
U (m/s)	25.13	37.70	50.27
α_1 (deg)	0.00	0.00	0.00
ΔP_0 (pa) (required)	1000	1000	1000
P_{01}	101325	101325	101325
P_{02}/P_{01} (required)	1.0099	1.0099	1.0099
ΔT_0 (K) (required)	1.0467	1.0467	1.0467
C_{w1} (m/s)	0.00	0.00	0.00
Forced vortex Constant, $b=C_{w2m}/r$	189.8	189.8	189.8
C_{w2} (m/s)	18.98	28.49	37.96
C_a (m/s) (Forced vortex)	32.83	36.69	41.49
Ca/U	1.31	0.97	0.83
β_1 (deg)	37.43	45.78	50.46
β_2 (deg)	10.61	14.12	16.52
$\Delta\beta$ (deg)	26.82	31.66	33.95
α_2 (deg)	30.03	37.81	42.46
DOR	0.62	0.62	0.62
Specific Work	1051.92	1051.92	1051.92
V_1 (m/s)	41.35	52.61	65.18
V_2 (m/s)	33.41	37.83	43.28
V_2/V_1	0.808	0.719	0.664
chord, c (m)	0.1	0.1	0.1
height, h (m)	0.1	0.1	0.1
A.R	1	1	1
No of Blades	15	15	15
Pitch, s (m)	0.0419	0.0628	0.0838
Solidity, ($c/s = \sigma$)	2.39	1.59	1.19
DF	0.29	0.45	0.58
Incidence (deg)	2	0	-2
m	0.3060	0.2990	0.2942
Camber, θ (deg)	30.95	41.50	49.19
Deviation, δ (deg)	6.13	9.83	13.25
Stagger, ζ (deg)	19.96	25.03	27.87

So, if you will be putting this number, this is what is giving me the idea about the variation of different parameters from hub to tip; say, we will be taking these three stations. If we are comparing here, what we have done? We have opted for say force vortex concept and because of say force vortex, we will be having our variation of C_{w2} based on our constant. Now, because of variation of my C_{w2} and because of this force vortex, my axial velocity, that's what is going to change. At the same time, my number that's what is C_a by U that is also changing because my axial velocity at the hub is changing, my axial velocity at tip is changing, okay. We can target our degree of reaction here; in this case, this is what is coming to be constant 0.62. We can say our relative velocity ratio is coming 0.80 and 0.66.

If you look at carefully, my $\Delta\beta$ what we are targeting near the hub, it is coming 26.82. That's what is very low compared to what all designs we have discussed up till now. But at the same time, that's what is say having slightly on higher side towards the tip region. We can say our degree of say diffusion factor, that's what is varying from 0.29 to 0.58 and here also, as we have discussed, our incidence angle that's what we have assume to be say $+2$ at the hub and -2 at say tip and at mid station we have taken that to be 0.

Now, this is what will give us the fundamental understanding in sense of how my flow parameter that's what is varying at hub, mean and tip, okay. Here, we need to be very careful with say use of the formula. Here, we are not having flexibility what we were discussing in sense of our fundamental method, okay. So, whatever numbers that's what is coming, that's what will be based on what equation you have selected with, okay. So, little careful and putting the equation in excel sheet and finding these parameters.

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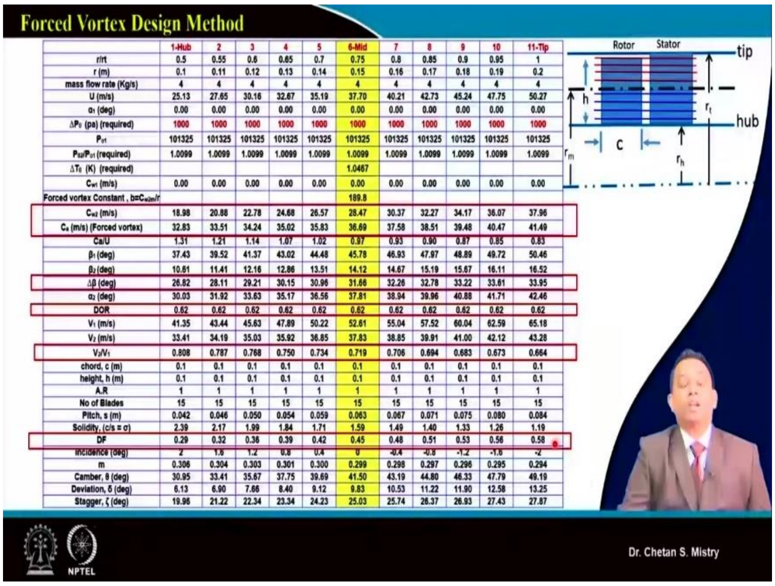

Now, if we will be putting this, this is what is giving us in sense of variation throughout my span for 11 different stations. And here if you look at, this is what it says, if you look carefully, we will be having a gradual variation that's what is happening for my axial velocity along my say radius. So, you can see, it is 32.83 and that’s what is varying to 36.69 at the mid station and 41.49 near the tip region, okay.

Same way, this $\Delta\beta$, that’s what we can see that is also varying in a systematic way, okay. So, unlike what we have done for our say fundamental method that’s where ΔP_0 what we are assuming, we need to take care of how this flow angles are varying, how my $\Delta\beta$, that’s what is varying. Since, this is what is say fixed with my radius; so, we will not be having that much complexity in sense, but, listen carefully when we are using our fundamental method, we can decide which station we want to highly load or say low load, okay; that’s what is a great flexibility that’s what we are having; that flexibility we are not having for free vortex as well as for force vortex design.

Now, you can see my degree of reaction, that’s what is coming 0.62. We can say our relative velocity ratio, that’s what is coming slightly lower near the tip region and my diffusion factor, you can say it is 0.29 and by diffusion factor at the tip, that’s what is coming to be slightly on higher side. It is more tip loaded kind of configuration, okay.

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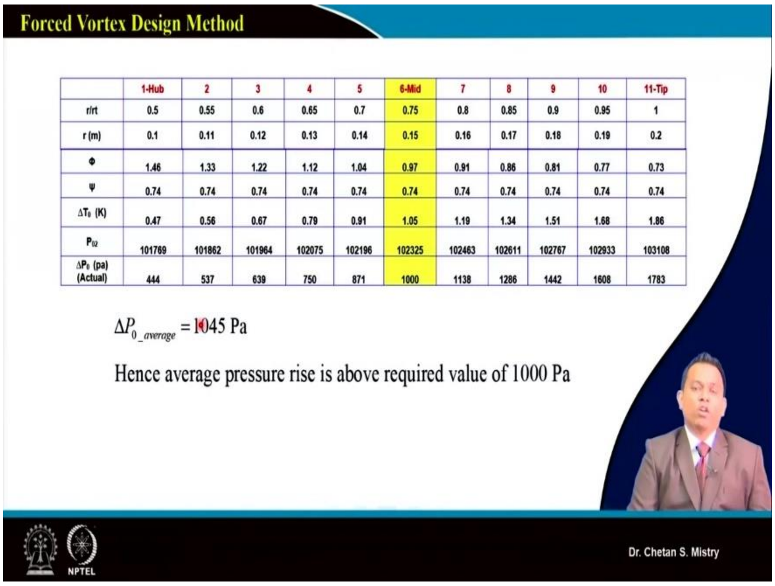

Now, this is what is very important. Once you are doing all this calculation, we have seen, we can calculate what will be our ΔT_0 at the hub, we can calculate what will be our ΔT_0 at the tip. Based on that you can calculate what will be my ΔP_0 and we can say my total pressure rise at the exit of my rotor, that’s what we will be getting by averaging out along this span. And, if you look at, we are expecting our pressure rise to be 1000 Pa, here this is what is coming 1045 Pa, okay.

So, this is also one of the cross checks in that sense, you can verify this part. Now, this is how we are doing our design for the rotor. Now, this is what if you are doing carefully, if you are putting your formulation carefully, if you are doing your excel sheet calculation carefully, this is what is the method that's what will be giving us what we are looking for in sense of expected performance, okay.

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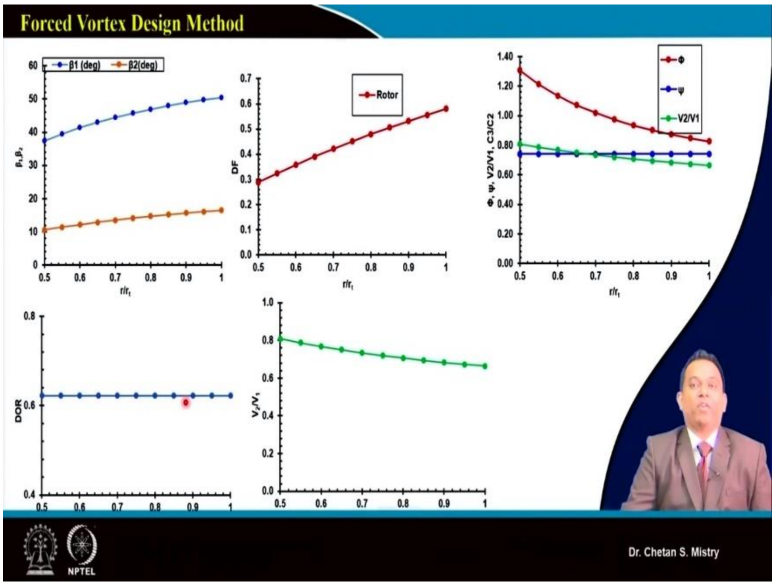

Now, in order to do the design for our say stator, we will be seeing here how we are looking at the variation of our angles. So, here in this case, if you look at carefully, say this is what is representing my β_1; unlike earlier case, where β_1, that's what was coming to be constant because my C_a and U for both the methods that's what was same. Here in this case, since my C_a, that's what is changing and that is the reason why we are having this variation. So, if you compare $\Delta\beta$ in this particular region at the hub and $\Delta\beta$ near the tip region, that's what is giving say, you know, not much variation that means the blade what we will be making it will be less twisted, okay.

So, many times as per the requirement, maybe you are not looking for say highly twisted blade; this is what is the configuration. And, if you compare, this is what is say higher diffusion factor near the tip region and degree of reaction, that's what is coming to be constant, okay. So, this is what will give us idea in sense of how my variation of degree of reaction, my $\Delta\beta$ and diffusion factor, that's what is happening. We will see the comparison of all the three method that will give more clarity, more clear picture for the comparison part.

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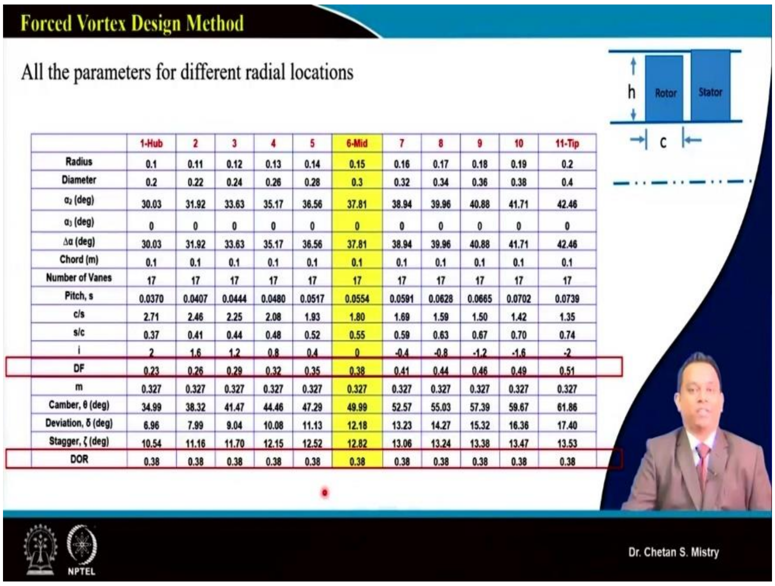

Now, in order to do the calculation for the stator we can use the same approach what we have opted for earlier two methods and there is no point in repeating the same steps here. You can see, we are calculating our mid station, okay…these are the mid station calculation. Now we are assuming our velocity…absolute velocity coming out from the rotor and absolute velocity entering inside my stator that's what is to be same.

And our exit, that's what we are assuming to be axial. And under that configuration if you are looking at, that's what will be giving me the variation of $\Delta\alpha$, okay. So, here if you look at my diffusion factor, that's what is coming to be 0.23 near the hub region and near the tip, I am having this number to be 0.51, okay. And degree of reaction as we have discussed, this is nothing but $1 - DOR_r$, that's what is coming 0.38.

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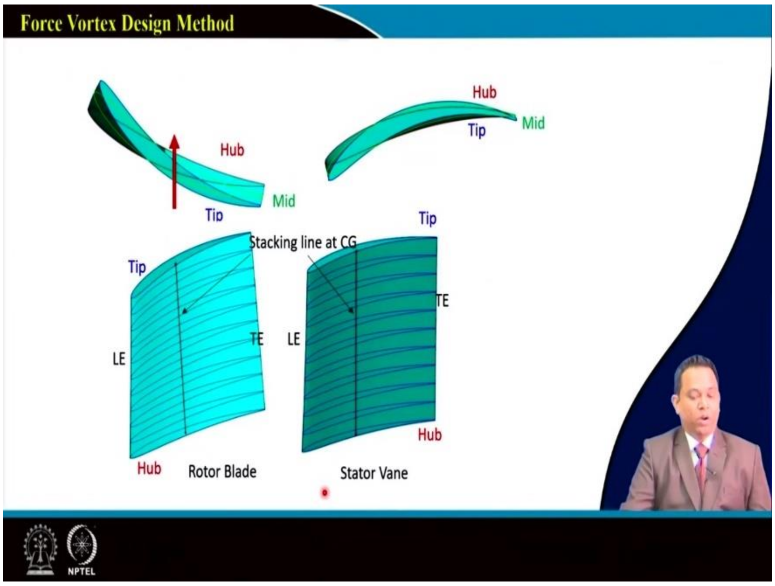

Now, just look at this part. So, this is what is representing our blade, when we are doing design using our force vortex concept. So, if you look at carefully, the twist we were discussing, that's what is coming to be lower. Same way for hub also we will not be having great turning that's what is happening for the stator. So, here near the hub region, my $\Delta\beta$, that's what is coming to be lower even near the tip region also we are not having this $\Delta\beta$, that's what is coming to be large, okay. So, this is what is giving less twisted blade, okay. And, both of them they are being stack about the CG.

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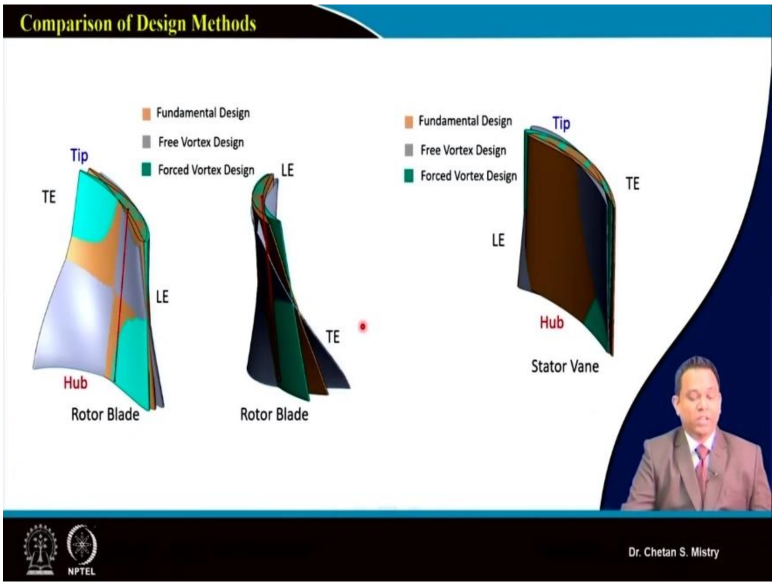

Let us…let us look at what is happening in sense of when we have comparing these three methods, okay. Here in this case, if we look at, this is what is going idea about say fundamental method, free vortex method and forced vortex method. Just look at, say this is what is representing my force vortex. So, in sense of comparison, you can understand my $\Delta\beta$, that's what is coming to be lower, okay. So, the twist for my blade, that's what will be lower when we are using our force vortex concept.

For free vortex concept we have realized, near the hub region, we are having our $\Delta\beta$ is coming to be larger and at the tip that's what is say slightly lower, it gives large twist to your blade, okay. Same way, here if we are looking at say for fundamental approach, free vortex and force vortex approach, we will be having our stator that also is less twisted, okay.

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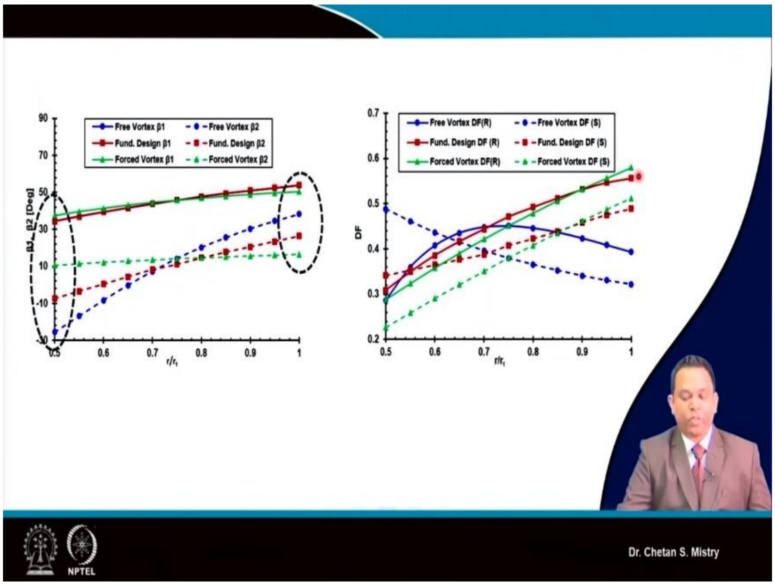

Let us see in sense of comparing all the three methods, what all we have discussed up till now. So, here in this case, if you are looking at this green color, that's what is representing my force vortex approach. And if we compare, we have seen, suppose say this blue color one, that's what is representing my free vortex design concept; red color one, that's what is representing my fundamental method. And this is what is representing my say force vortex approach.

And if we look at, my $\Delta\beta$ here, that's what is not varying much from hub to tip, okay. And, my β_1, that's what is varying, because my axial velocity is going to vary, okay. Now, here in this case, if you are comparing say diffusion factor for both stator as well as for the rotor, we are having say diffusion factor to be slightly lower near the hub region, but it is higher towards say tip region, that's what is giving us idea about tip loaded kind of configuration.

So, when we are comparing say our fundamental method and force vortex method, my diffusion factor, that’s what is coming to be lower. But at the same time, if you are comparing near the tip region, we are having this diffusion factor it is nearby to what all we have discussed about the fundamental method, okay.

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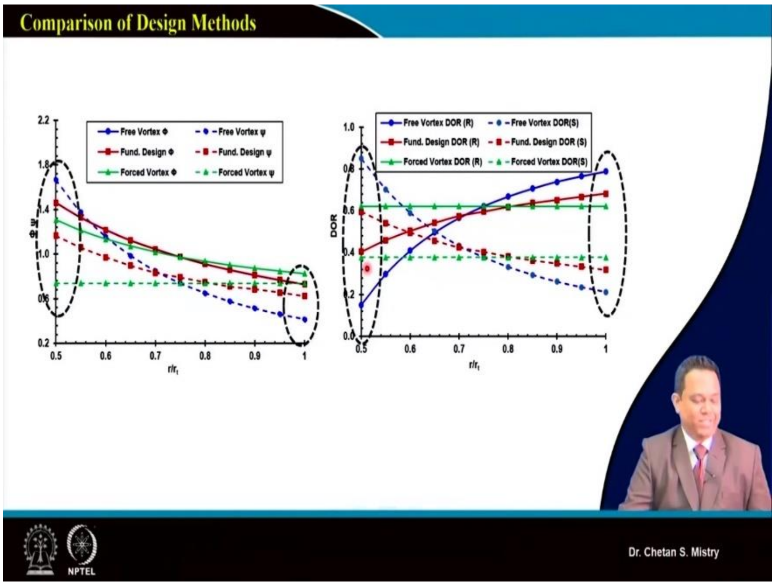

Now, if you are comparing what is happening with our say flow coefficient, as we have discussed, that’s what is varying with variation of axial velocity. So, near this region, if you are comparing say, this is what is representing what is happening with my loading. So, this dotted line if you are looking at this is what is giving a constant kind of configuration, okay. And if you are comparing our degree of reaction, you can say, we have great variation of degree of reaction, that’s what is happening for the free vortex near the hub region as well as near the tip region.

When we are looking at say fundamental approach, for that my degree of reaction variation that’s what is coming to be slightly lower compared to free vortex approach. But for say this, our force vortex approach, we can realize degree of reaction, that’s what is coming to be constant.

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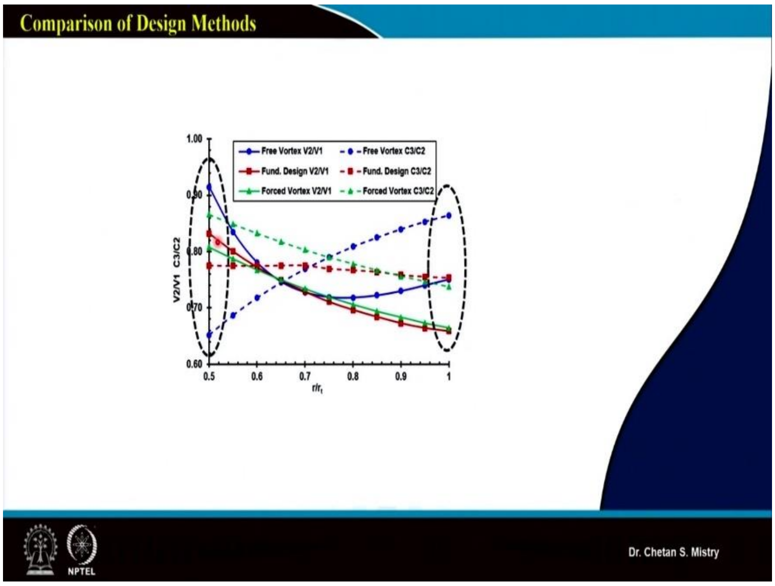

And this is what is representing what is happening with my De Haller’s number. And if you are comparing this say relative velocity ratios, okay; for say our free vortex approach, this is what is showing the variation from hub to say our tip or say shroud, when we are comparing our case for say force vortex concept, that variation is not that drastic, okay. We can see, this is what is say nearly same kind of configuration we are getting in line to what we are discussing about say our fundamental method.

So, this is what is all, that’s what is giving us an idea about say comparison of these three-design method. You can try with other design approaches also, okay. But we need to realize the thing is what you are doing, that’s what should give what we are expected in sense of performance, in sense of pressure rise, in sense of efficiency. And later on, we are also interested in what we say is in terms of say operating range.

Now, let me tell you people they are talking about different softwares, which is taking care of optimization. Now, you can understand, say you are optimizing by say different kinds of approaches, what you are opting for, maybe that’s what will be giving you what you are looking in sense of performance at one point, that’s what is my design point, but it may be possible during off design condition, it may go worst.

So, as and when you are doing your design, do that design carefully. Now, we are having availability of open source softwares also; you can use open source software for say numerical simulation, you can check with what all we are discussing at this moment, you can compare your flow physics by these three methods.

Now, data sheet is with you, you are having say equations for making of airfoil that is also with you. So, everything that's what is now in open. So, it is you who need to decide with what you will be doing with using this all data what we are sharing at this moment. So, what all that's what is available in open book, they people, they are talking about design at the mid station and maybe talking designed at say hub and tip, but you need to be careful and you must have realized it is not only that three station, that's what is very important, all the stations based on number of say equal division what you are making for span they are important, okay.

So, here we are stopping with, today we are going to stop our design for low speed axial flow compressor based on availability of data, maybe from research paper, you can start practicing. Now, in sense of having say your examination, we will be giving some of the data and based on that data you need to do calculation using say one of the method and you need to share with what we say mid station calculation and your design excel sheet.

So, thank you very much and I hope you have enjoyed the design for low speed axial flow compressor. From next lecture we will start discussing about design of contra rotating fan. Thank you. Thank you very much for your presence!