Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture 41
Design Low Speed Compressor (Contd.)

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Hello, and welcome to lecture 41. We are discussing about the design of low speed axial flow compressor. In last sessions, we were discussing about the design of low speed axial flow compressor using two different approaches; first, that's what is by using say free vortex concept and we started talking about the fundamental approach.

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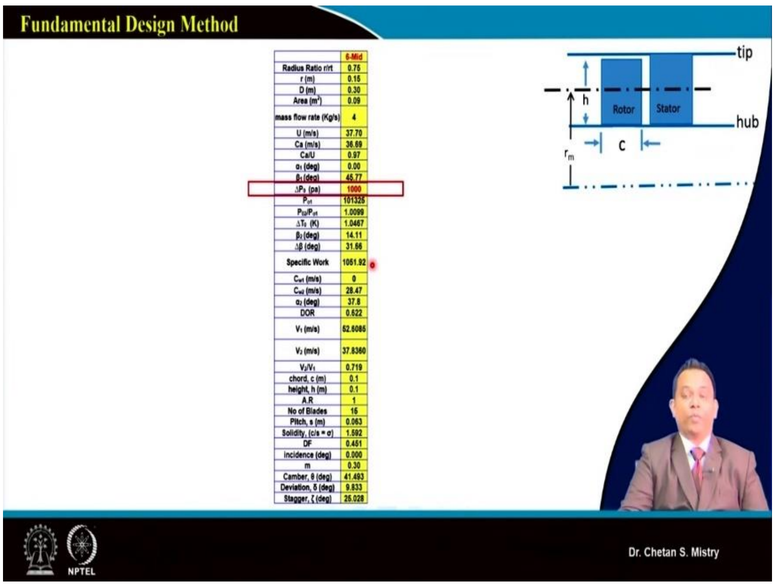

So, for fundamental approach, we are taking our mid station calculation, that's what is similar to what all we have done for free vortex concept; by considering our total pressure rise to be 500 at the mid station and based on that we have done our fundamental calculation of different velocity components, different flow angles, degree of reaction, diffusion factor, De-Haller's factor, we also have calculated different flow angles, say incidence angle, deviation angle, camber angle, stagger angle. So, at mid station all these numbers they are known to us now.

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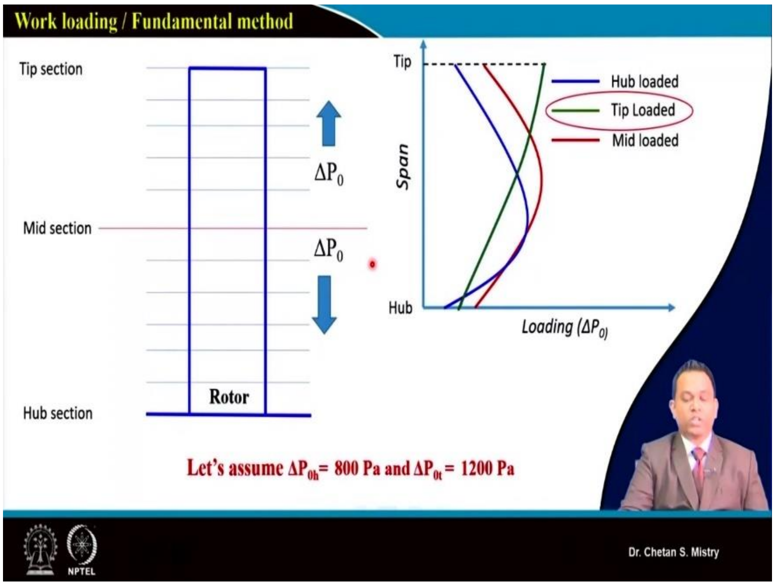

Now, as we have discussed during our class session, in order to use this fundamental approach, we are having three different possibilities, like we can go with say hub loaded design configuration, we can go with mid loaded configuration and we can go with say tip loaded configuration. So, here if you look at these are the different approaches what we have discussed. Now, in order to go for say design approach say at mid station, we have done our calculation for all flow angles, all velocity components, everything.

Now, what all we have used is we have compared our aerodynamic work and thermodynamic work and based on that we have calculated what will be our exit whirl component. Similarly, here in this case, what we will be doing at hub we will be taking say our pressure rise expected total pressure rise to be 800 Pa and 1200 Pa.

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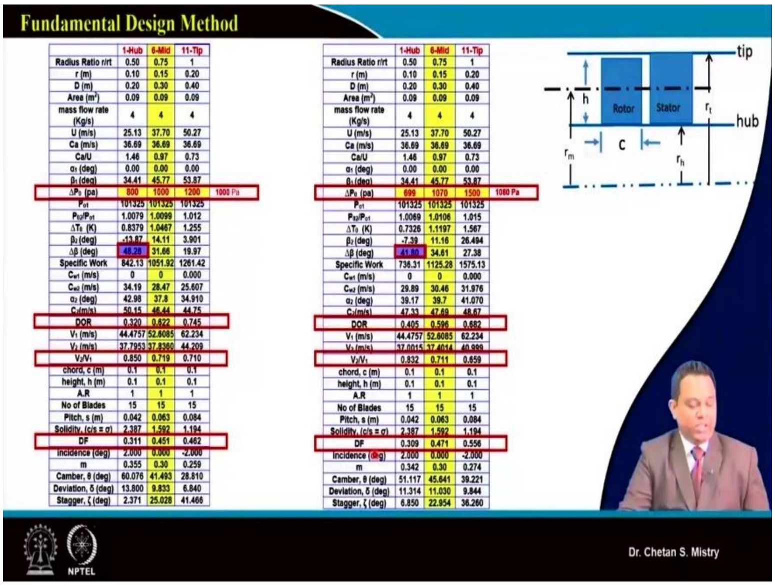

And for that, we have discussed the approaches. So, here, this is what is based on what all assumptions we have done; say at mid station, we are having say total pressure rise of 1000 Pa, at hub station, we have assumed that to be 800 Pa and near tip we have assumed that to be 1200 Pa. And then, as we have discussed, we need to look at the parameters and their variation.

So, what observation we found is $\Delta\beta$ near the hub, that's what is coming to be slightly on a larger or say it is more than 45°. So, that is where we feel we need to have some control or we need to do some modification. If you look at say degree of reaction, that's what is say coming to be lower, it is 0.32 at the hub; we are having our relative velocity ratio it is 0.85, it is a little high on that side; we have our diffusion factor to be 0.31.

Now, as we have discussed all designs what we will be doing for axial flow compressor let it be low speed compressor or let it be high speed compressor, we will be using our fundamental approach using say excel sheet design. Here, as we have discussed, we will be having all flexibility to do modification and immediately we will be having cross check or say variation in number visually. If we are doing coding for making the design program that is also one of the possibilities but there we will be having number of sheets that will be generated, that's what ultimately you need to check with. So, it is better we will be doing this using say excel sheet program.

Now, here in this case, say what rotor we are designing, we will be providing some clearance between casing and my rotor tip. When we are providing that clearance, we learn that's what will be subjected to some losses and those losses we have defined as say tip clearance loss.

And that's what is a major contributor in sense of total pressure loss or pressurizing capacity of my stage. So, in order to take care of that, what we will be doing, in place of designing for 1000 Pa. Let us try or putting that on slightly on higher side…say maybe say 1080 Pa and in order to do that, we have modified our ΔP_0 at hub to be 699, at mid station also we have modified now, in spite of say 1000, we will be taking 1070 and at the tip we will be taking 1500 Pa.

So, in overall if we look at, we are getting our total pressure rise, that's what is coming 1080 Pa. Now, when we are doing this modification what will happen? That's what is giving me my $\Delta\beta$, that's what will be reduced from 48 to 41. So, this is what is the flexibility what we have by using this excel sheet program, okay. At the same time, we can see, our degree of reaction, that's what has increased to 0.40 and relative velocity, that's what has reduced slightly say 2.83 and diffusion factor we can say it is 0.309.

As we have discussed, here we can do modification in sense of say number of blades also, since we are maintaining our uniformity for all the three design approaches. So that, we will be having one to one comparison, that's why we are not changing but you can understand; suppose if I am looking for say my diffusion factor to be in the range of 0.6, accordingly I will be changing my number of blades, okay.

Because we know, diffusion factor, that's what is a function of my solidity and solidity we are defining as say chord to pitch. So, with change of my number of blade or by changing my chord, we are able to modify our solidity and that's what will be reflected in sense of change of diffusion factor.

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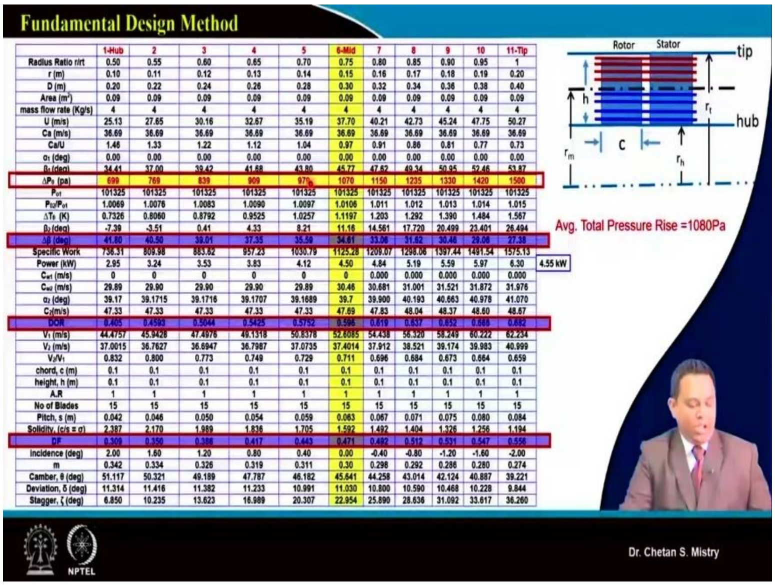

So, with this, let us try to divide this into different 11 stations what we have done. So, here if we look at, we have divided that into equal number of stations. As we have discussed, say it is in the interval of 0.01 meter and again I am telling you suppose say if you are looking for say more accurate or more precise design, that time you need to go with more number of stations. Suppose say this is what is low aspect ratio blade; so, you can say, my height of the blade is say smaller. It may be possible that you will be having taller blades; for taller blades, you increase your number of stations. So, variation of my blade geometry that's what will be taken care more precisely in that case, okay.

Now, here unlike what we have done for our say free vortex concept where everything that's what was depending on my constant and radius. So, radius, that's what was remaining constant. And that is the reason why what all we are getting, that's what we were accepting. Now, here in this case, what we have flexibility? If we look at this ΔP_0, I can vary in sense of numbers.

Now, what all we need to check is how my angles are changing, listen me carefully here. So, here if you look at, just keep on eye here, say you are putting this number at hub. So, you will be getting your $\Delta\beta$, okay. Now, say next I will be putting in sense such that I will be having, say some particular trend for variation of β_2 or say $\Delta\beta$.

Since, my β_1, that's what is a function of Ca by U that's why we are not finding much change there. Here, this is what is in our control. And, that is the reason why we need to be very careful in sense of selecting this number, do not get confused, this is what is based on number of iterations, number of trials, okay. Maybe you can put one plot here, where you can put say change of your radius along with that you just put what will be your $\Delta\beta$ or maybe you can put one of the observed parameters; say, degree of reaction or maybe you can put say one parameter say diffusion factor; it is your choice, but that need to have particular trend, okay.

Suppose, say if you will be having these numbers coming to be zigzag, say here at hub, suppose I have taken 699, immediate station I can take 800 also. But we need to understand when I am doing my averaging that should come what we are expecting, okay. At the same time, what numbers you are putting near the tip region, that's what you need to keep on eye with your diffusion factor, okay. Suppose say if I am changing this number, that's what will be changing my diffusion factor. So, you can have two observations, you need to have two observation.

First, that's what is near the hub region. And second, that's what is near the tip region. Now, suppose say when you are doing your iterations by putting different numbers, it may possible that near a mid-station you will be having some kind of say droop or maybe it will be having upside kind of trend. So, just adjust that number, it is designer's choice, it is your choice, you need to decide with that number, okay.

So, that is how this numbers they are been selected with. Now, since we have arranged it in a systematic way, you can see, we are having this $\Delta\beta$, that's what is having particular trend, okay. Same way here, diffusion factor also, you will be finding a particular trend, we are having say keep an eye for say degree of reaction, that's what is varying from 0.4 to 0.68.

Even at the same time, say our De-Haller's factor, that's what is varying from 0.83 to 0.65. So, near the tip region, this De-Haller's number, that's what is having say slightly on a lower side, but that's what is accepted in the sense, okay. It is preferred that you will be going with this number to be slightly higher. But by doing that, maybe you need to play with the other numbers and you need to keep on eye. So, whole this sheet or whole design, that's what is been based on what number we are selecting for this ΔP_0, okay. Now, this is, what is a very great flexibility to the designer, okay.

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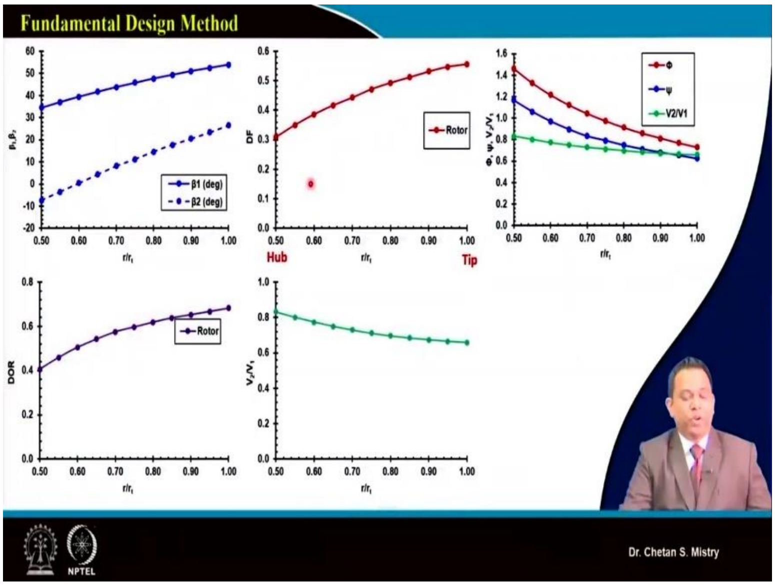

Now, once we are putting all this together, that's what is giving me my variation of $\Delta\beta$. So, here if you look at, this is what is say my β_1 angle and if you compare to our free vortex, here my $\Delta\beta$ at hub, that's what is slightly lower. And at the tip, that's what has increased in the trend. Again, say what ΔP_0 what you are selecting at different station, based on that $\Delta\beta$, that's what is in your control; you can adjust your $\Delta\beta$, you can put as per your expectation as per your requirement, okay. If you are looking for a highly twisted blade, you are looking for low twisted blade, accordingly we need to check with, okay.

Now, here in this case, this is what is representing my diffusion factor and as we have discussed, that's what is showing me higher diffusion factor near the tip region and comparatively low…compared to your tip, that's what is say on lower side, that's what is at the hub. Now, this is what is representing how my velocity components, loading coefficient and flow coefficient that's what is varying and this is what is at say degree of reaction.

You can see, my degree of reaction, that's what is varying from 0.4 to 0.68, okay. Now, this is what will give idea about the selection of this number. So, when you are making your excel sheet program that time maybe you can put this kind of plot side by. So that, you will understand what is a trend, what you are looking for, is it coming or not, okay?

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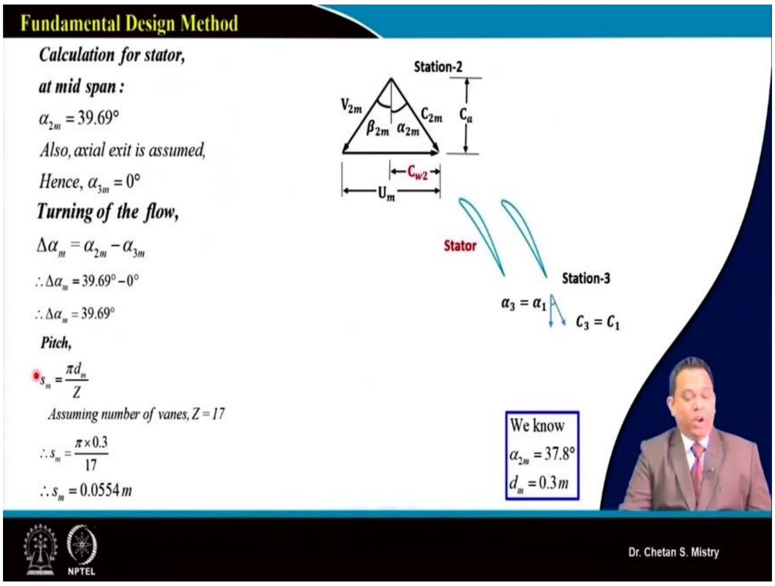

Now, based on that in our next step, that's what will be to design say our stator. And for stator, what we have learned for say stage configuration, rotor-stator combination, we are assuming our absolute velocity coming out from the rotor, that's what will be equal to say our velocity…absolute velocity at the entry of my stator.

So, we can say, what is my α_2 coming out from the rotor, that's what will be the entry for my stator, that is the reason we are putting here this α_{3m}, that's what is 0, that's what is at the exit and α_{2m}, that's what is 39.69.

$$Calculation\ for\ stator,$$

$$at\ mid\ span:$$

$$\alpha_{2m} = 39.69°$$

$$Also, axial\ exit\ is\ assumed,$$

$$Hence, \alpha_{3m} = 0°$$

Remember, we have modified our mid station and that's the reason why we need to put this set. Say, for earlier calculation for free vortex, there we have taken at mid station the pressure was 1000 Pa and here, this is what is 1070 Pa.

And, as the reason why we are having our α or $\Delta\alpha$, that's what will be different at the mid station. So, be little careful in sense of doing the calculation. So, once we are calculating this $\Delta\alpha$, that's what is coming 39.69.

$$Turning\ of\ the\ flow,$$

$$\Delta\alpha_m = \alpha_{2m} - \alpha_{3m}$$

$$\therefore \Delta\alpha_m = 39.69° - 0°$$

$$\therefore \Delta\alpha_m = 39.69°$$

Now, our next target that's what is to calculate what is our diffusion factor? And that's what we are calculating based on my pitch and chord, we are basically calculating our solidity.

So, here my pitch, that's what is given by this is what we are calculating at the mid station. So, we will be taking carefully diameter at the mid station and number of blades here we have taken as say 17, okay. So, that's what we will be giving me my pitch to be 0.055 meter.

$$Pitch,$$

$$s_m = \frac{\pi d_m}{Z}$$

$$Assuming\ number\ of\ vanes, Z = 17$$

$$\therefore s_m = \frac{\pi \times 0.3}{17}$$

$$\therefore s_m = 0.0554\ m$$

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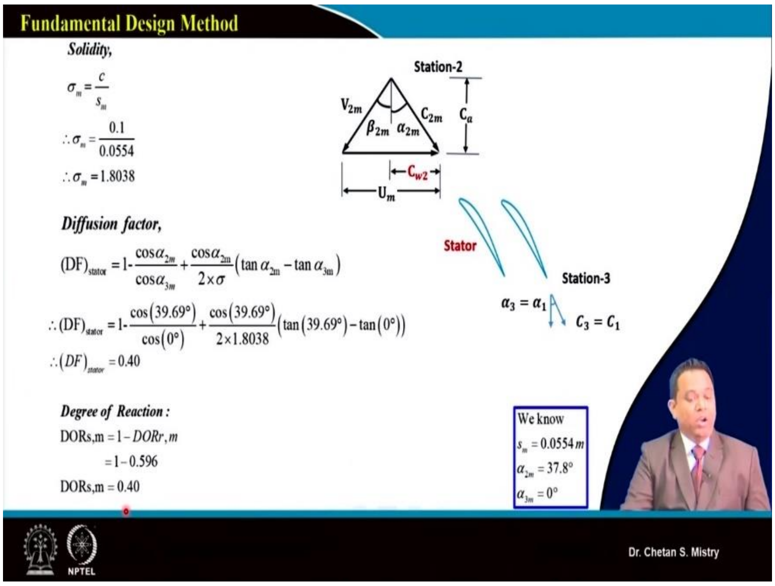

Now, based on our available chord, that's what is say 0.1 meter, we can calculate what will be our solidity at mid station and we can calculate what will be the diffusion factor for the stator. Again, this is to remind what angles we are putting for rotor we are taking basically relative flow angles, here we need to take absolute flow angles, that's what is a change in the formulation, okay.

$$Solidity,$$

$$\sigma_m = \frac{c}{s_m}$$

$$\therefore \sigma_m = \frac{0.1}{0.0554}$$

$$\therefore \sigma_m = 1.8038$$

$$Diffusion\ factor,$$

$$(DF)_{stator} = 1 - \frac{\cos\alpha_{2m}}{\cos\alpha_{3m}} + \frac{\cos\alpha_{2m}}{2\times\sigma}(\tan\alpha_{2m} - \tan\alpha_{3m})$$

$$\therefore (DF)_{stator} = 1 - \frac{\cos(39.69°)}{\cos(0°)} + \frac{\cos(39.69°)}{2\times 1.8038}(\tan(39.69°) - \tan(0°))$$

$$\therefore (DF)_{stator} = 0.4$$

If you are calculating our diffusion factor for the stator, that's what is coming point 0.40, okay. And, degree of reaction as we have discussed, that's what we can say it is $1 - DOR_{r,m}$. So, that's what is giving me my say degree of reaction to be 0.4, okay.

$$Degree\ of\ Reaction:$$

$$DOR_{s,m} = 1 - DOR_{r,m}$$

$$= 1 - 0.596$$

$$DOR_{s,m} = 0.4$$

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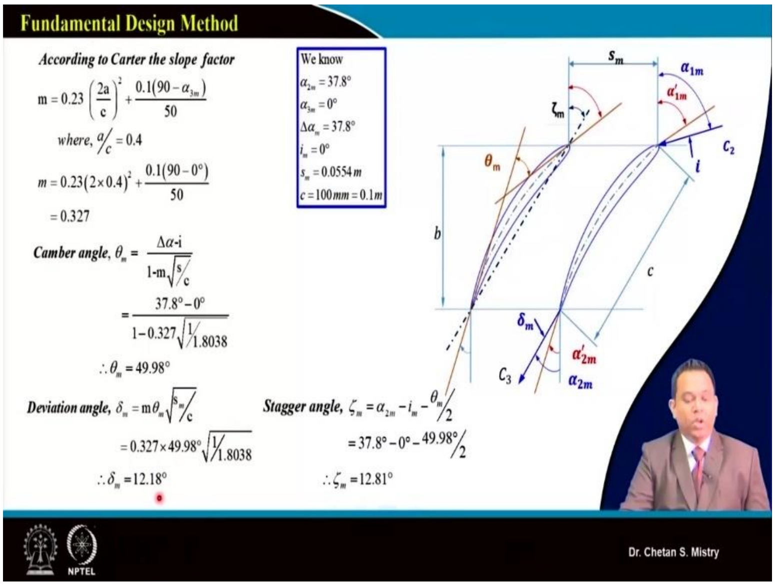

Now, we need to check with the angles that's what say what is my say camber angle? What will be my deviation angle, what will be my stagger angle? So, those we are calculating based on Carter's parameter or 'm' factor. So here in this case, this 'm' factor that's what is coming 0.327.

$$According\ to\ Carter\ the\ slope\ factor,$$

$$m = 0.23\left(\frac{2a}{c}\right)^2 + \frac{0.1(90 - \alpha_{3m})}{50}$$

$$where, a/c = 0.4$$

$$m = 0.23(2 \times 0.4)^2 + \frac{0.1(90 - 0)}{50}$$

$$= 0.327$$

We can calculate what will be our camber angle, that's what will be $\Delta\alpha$; in the case of my rotor, we are taking $\Delta\beta$ and this is what is my incidence angle.

Let me tell you, at mid station for stator we are assuming our incidence angle to be 0, okay. So, this is what is say and if you will be putting this, this is what will be giving me my δ say deviation angle, okay. We can calculate our camber angle, we can calculate our deviation angle and based on this formulation, we can calculate what will be our stagger angle, okay.

$$Camber\ angle, \theta_m = \frac{\Delta\alpha - i}{1 - m\sqrt{\frac{s}{c}}}$$

$$= \frac{37.8° - 0°}{1 - 0.327\sqrt{\frac{1}{1.8038}}}$$

$$\therefore \theta_m = 49.98°$$

$$Deviation\ angle, \delta_m = m\theta_m\sqrt{\frac{s_m}{c}}$$

$$= 0.327 \times 49.98°\sqrt{\frac{1}{1.8038}}$$

$$\therefore \delta_m = 12.18°$$

$$Stagger\ angle, \zeta_m = \alpha_{2m} - i_m - \frac{\theta_m}{2}$$

$$= 37.8° - 0° - \frac{49.98°}{2}$$

$$\therefore \zeta_m = 12.81°$$

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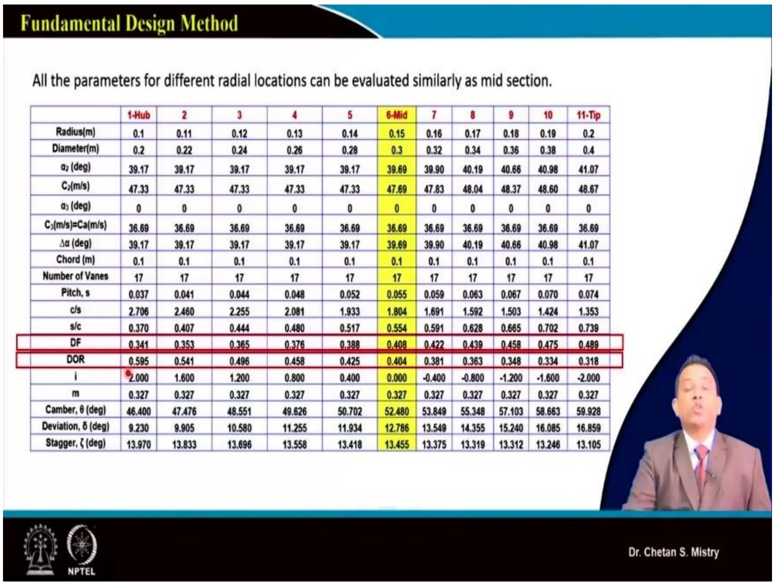

	1-Hub	2	3	4	5	6-Mid	7	8	9	10	11-Tip
Radius(m)	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.2
Diameter(m)	0.2	0.22	0.24	0.26	0.28	0.3	0.32	0.34	0.36	0.38	0.4
α_2 (deg)	39.17	39.17	39.17	39.17	39.17	39.69	39.90	40.19	40.66	40.98	41.07
C_2(m/s)	47.33	47.33	47.33	47.33	47.33	47.69	47.83	48.04	48.37	48.60	48.67
α_3 (deg)	0	0	0	0	0	0	0	0	0	0	0
C_3(m/s)=Ca(m/s)	36.69	36.69	36.69	36.69	36.69	36.69	36.69	36.69	36.69	36.69	36.69
$\Delta\alpha$ (deg)	39.17	39.17	39.17	39.17	39.17	39.69	39.90	40.19	40.66	40.98	41.07
Chord (m)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Number of Vanes	17	17	17	17	17	17	17	17	17	17	17
Pitch, s	0.037	0.041	0.044	0.048	0.052	0.055	0.059	0.063	0.067	0.070	0.074
c/s	2.706	2.460	2.255	2.081	1.933	1.804	1.691	1.592	1.503	1.424	1.353
s/c	0.370	0.407	0.444	0.480	0.517	0.554	0.591	0.628	0.665	0.702	0.739
DF	0.341	0.353	0.365	0.376	0.388	0.408	0.422	0.439	0.458	0.475	0.489
DOR	0.595	0.541	0.496	0.458	0.425	0.404	0.381	0.363	0.348	0.334	0.318
i	2.000	1.600	1.200	0.800	0.400	0.000	-0.400	-0.800	-1.200	-1.600	-2.000
m	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327	0.327
Camber, θ (deg)	46.400	47.476	48.551	49.626	50.702	52.480	53.849	55.348	57.103	58.663	59.928
Deviation, δ (deg)	9.230	9.905	10.580	11.255	11.934	12.786	13.549	14.355	15.240	16.085	16.859
Stagger, ζ (deg)	13.970	13.833	13.696	13.558	13.418	13.455	13.375	13.319	13.312	13.246	13.105

So, once we are having all these numbers, that's what is coming with us, we can check with what all will be the changes, okay. So, here we are putting our observed parameter as say diffusion factor. So, you can say this is what is 0.34 and at the tip, that's what is coming 0.48. So, you can say, near the tip region your stator is highly loaded in that sense, okay. And other parameters we can say our degree of reaction, that's what we are calculating based on say $1 - DOR_{rotor}$. So, you can say my degree of reaction at hub, that's what is coming to be larger, okay.

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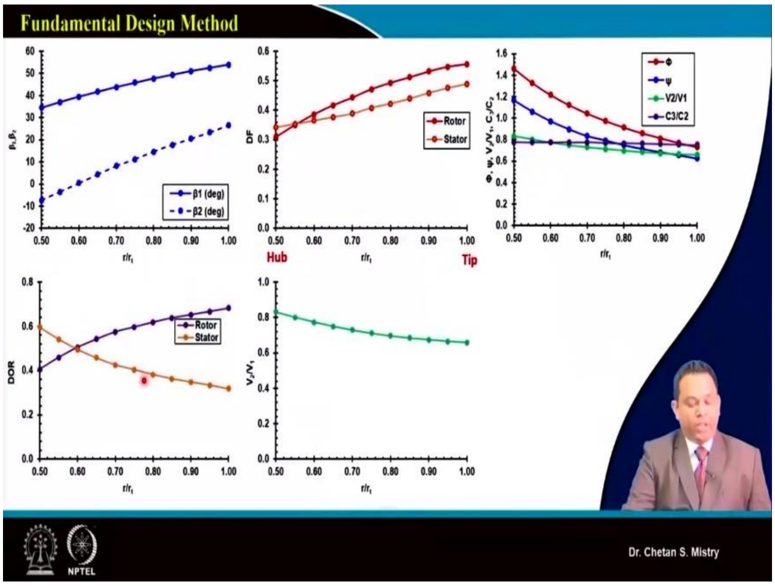

And, let us see what all changes we are finding in sense when we are incorporating the calculation of the stator. So, here in this case, if you look at my stator that's what is having say diffusion factor to be slightly on the higher side near the hub region; and near the tip region, that's what is say decreasing, okay. Same way here, this degree of reaction trend, that's what we have already compared with, okay. So, this is what is $1 - DOR_{rotor}$.

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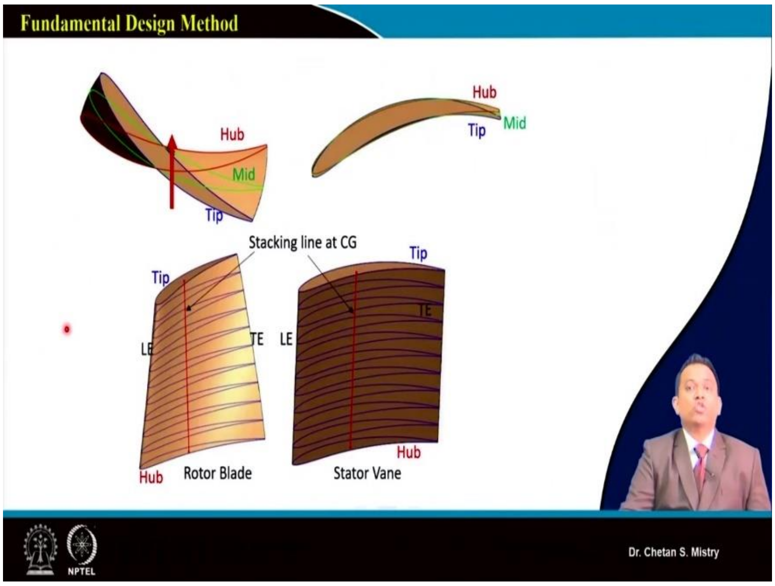

Now, this is what is giving us the idea about the calculation of all flow angles and based on that what all we have done. So, we can assume our airfoil to be C4, we are having now understanding of calculating x and y coordinate for the airfoil; for upper surface as well as for the lower surface. Since, we are using C4 airfoil, that's the reason we know the CG point, we know what is our stagger angle and based on that, we can do the calculation here, okay. And, we can generate our geometry. Now, interestingly here if you look at, this blade…rotor blade, that's what is having slightly lower twist compared to what all we have done for free vortex design, okay. Same way for stator also, this is what is a variation of my angles.

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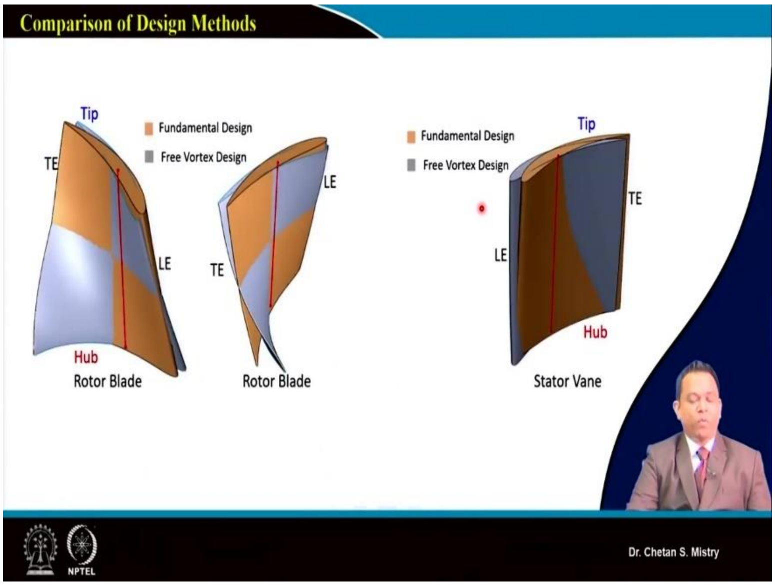

Let us try to compare one by one. Suppose say here if you look at, there are two plots; say if you look at this golden color, that's what is representing my fundamental approach and the silver color that's what is representing my say free vortex concept. So, for free vortex, as we have discussed, my $\Delta\beta$, that's what is coming to the larger near the hub region.

At the same time if you find near the tip also that angle that's what is coming to be slightly on higher side. So, that's what is giving say highly twisted blade; you can see this high twist from pressure side, same way we can look at say twist from the suction side. So, this is what is representing my fundamental approach and say other one that's what is representing my free vortex concept.

So, that is why! So, this is what is a designer's choice to opt for which kind of design method he or she will be opting for. Similarly, here if you look at, my angles for stator also they are going to change. Remember, for both the configuration our exit that's what we are assuming to be axial one, okay. So, this is what is giving us idea about how my blade geometries that will be changing.

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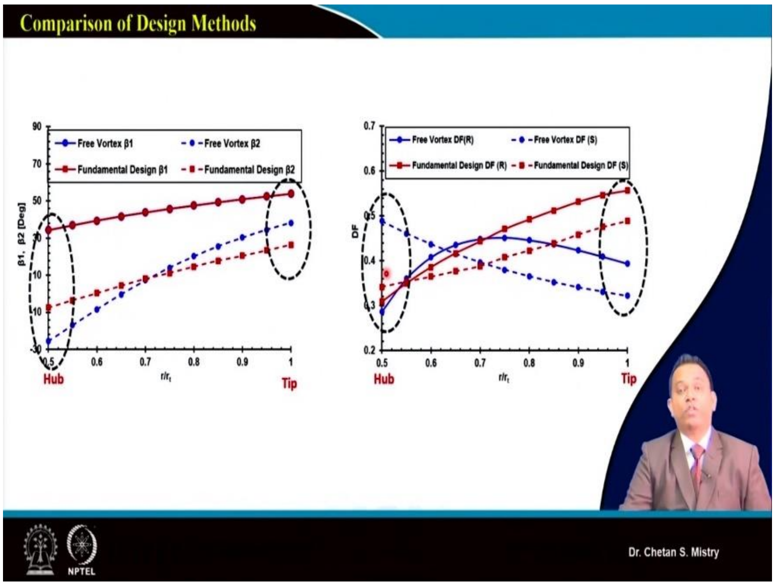

Now, let us try to compare what all we have seen from these two methods. So, here if you are comparing we are having free vortex method, we have our fundamental method. And as we have discussed, say this β_1, that's what will be same for both the methods, my β_2, we can see here, say here, in this case, when we are looking at β_2, using our fundamental approach my angle β_2, my exit angle, that's what is coming to be slightly lower, that's what is giving me my $\Delta\beta$ to be lower near the hub region, okay.

In line to that, if you are looking at near the tip region, that $\Delta\beta$, for say fundamental method, it is coming on higher side, basically that's what is representing our blade twist, it is less and that's what we have seen even in our 3D geometry for rotor blades, okay.

Now, here in this case, if you are comparing this is what is representing my diffusion factor. So, for free vertex concept, if you observe carefully, suppose say when we are talking about say rotor; so, my rotor, that's what is having say diffusion factor that's what was lower near the hub and that's what is higher on mid-section and that's what is lower near the tip region, okay.

So, just understand we say our diffusion factor that is nothing but that's what is representing my aerodynamic diffuser, okay. Now, if we take carefully say for stator, if you are observing, we will be having our diffusion factor to be larger near the hub region, just understand one thing, this $\Delta\beta$ what we are considering to be large for the rotor, that's what is reflecting here.

Your stator needs to do more amount of work near the hub region, because you are having great turning near the hub region for the rotor, okay. And, that is the reason why this is what is say you are having diffusion factor to be larger; near the tip region, that's what is coming to be lower.

Now, for the case of say our fundamental approach, we can understand that's what we have designed for tip loaded, it is reflecting here. What it says? My, say diffusion factor for both rotor and stator that's what is coming to be higher near the tip region, okay. So, this is what is one of the important observed parameter like what is happening with your say $\Delta\beta$, what is happening with your diffusion factor.

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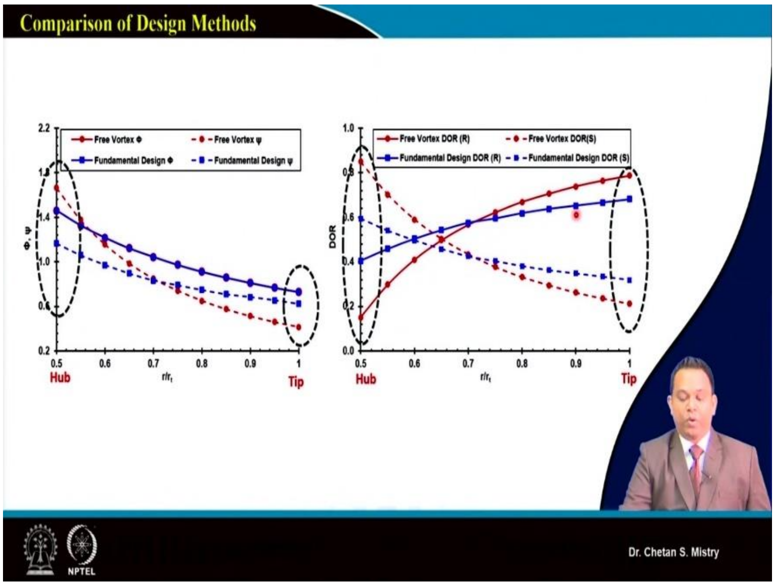

Now, let us see, suppose if you are considering what is happening with our, say ϕ and ψ? So, we can say, the value of our ϕ, that's what is not changing at this moment because my C_a value and my U value, that's what is same. But at the same time, when we are looking at say our loading coefficient, we can see for our fundamental approach, this is what is representing say systematic loading throughout my span, okay.

And if we absorbed here say for free vortex kind of configuration by loading that's what is changing all the way from hub to tip, okay. And inline to that, if you are looking at, this is what is representing my degree of reaction. And as we have discussed, degree of reaction, that's what is the presenting your thermodynamic diffusion. So, in line to what all we have discussed about the diffusion factor similar kind of trend that's what we are observing here.

And, here if you look at, my degree of reaction, if you are talking about the stator, that’s what is coming to be larger, okay; because your work that needs to be done by stator that’s what is on higher side. Now, similar trend if we are comparing with the both the methods, we are having good control in sense of my degree of reaction, we can say it is more in sense of tip loaded, that’s what has been reflected here in sense of variation, okay.

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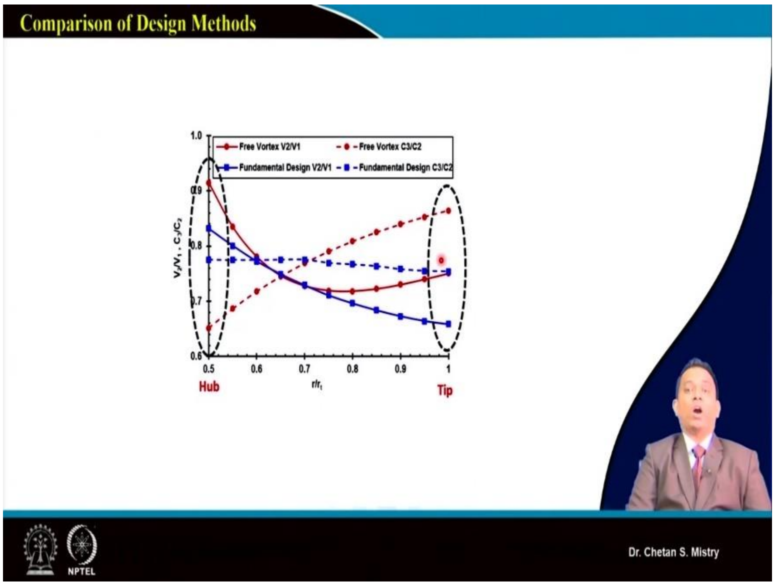

Now, this is what is representing our parameter we call say our De-Haller's factor. So, this De-Haller factor we have comparing for say free vortex, that’s what is very high near my hub region. And that’s what is going to change near the tip region. And if we are comparing here with say our fundamental approach, that’s what is saying my De-Haller's number that’s what is decreasing, but decreased that’s what is in a systematic way, okay.

Same way we will be having, say our variation of absolute velocity component, basically that’s what is representing my flow acceleration, okay. So here, if we look at my C_3/C_2 that’s what is coming nearly constant kind of thing. But for a free vortex concept, we can say we are having more acceleration of our flow that’s what is happening, that’s what is near the tip region, okay.

Now, this is what all we have discussed in sense of say, comparison for free vortex concept as well as we have discussed about say, our fundamental method. And what we realized is say free vortex concept that’s what is easy in sense of doing our calculation, but that has many constraints. Positive thing about the free vortex concept is it is satisfying our radial equilibrium equation, and that’s what is our need; but at the same time, when we are looking at say our blade twist near the hub region, that’s what is coming to be larger.

For this design our degree of reaction near the hub region that’s what was coming reasonably good, but in many designs, where you are having say hub diameter to be smaller, there may be possibility that degree of reaction will go negative.

So, that care we need to take care of; and in order to avoid such kind of situation and in order to have great control in sense of our operation, fundamental approach that’s what is giving more systematic way of designing, we have more control in sense of what we are expecting throughout our span. One more thing is more the number of stations we will be selecting, more smoother will be our curvature. At the same time when we are making our airfoil as we have discussed we need to select more number of points, very close points, maybe in sense of 1000’s.

So that, the curvature, when we are making by joining these points, that’s what we will be giving say continuous curve and without any zigzag, okay. So, I am sure, you people may be making your design excel sheet for solving this numerical. I prefer you do practice you are having.