Aerodynamic Design of Axial Flow Compressors and Fans
Professor Chetankumar Sureshbhai Mistry
Department of Aerospace Engineering
Indian Institute of Technology, Kharagpur
Lecture: 58
Design of Transonic Compressor (Contd.)

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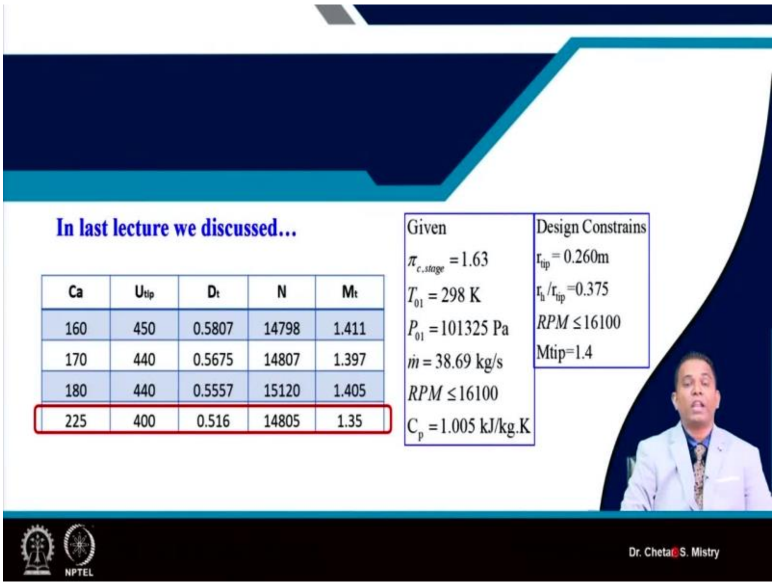

Hello, and welcome to lecture 58. So, continuing with the design discussion, we were discussing about the design using constant hub diameter configuration for the flow track, we have our axial velocity to be 225 m/s, peripheral speed to be 400 m/s. And, we are having certain constraints what we have discussed, that's what is in sense of say, tip diameter to be 0.260 hub to tip ratio at the end it to be 0.375. And our speed that should not exceed by, say 16,100.

Now, in next lecture, we started discussing about the distribution of ΔP_0 at the mid station. And, if you recall, that's what we have assumed to be slightly higher than what design pressure rise we are expecting, that's what is in order to iterate or say, maybe in order to reduce the number of iterations.

We have started doing calculation assuming same aspect ratio, same number of blades, in order to compare these two design methodologies. We have done our calculation, at the mid station for rotor, we have done our calculation for say, at hub station. Now, today we will be discussing doing calculation at a tip station.

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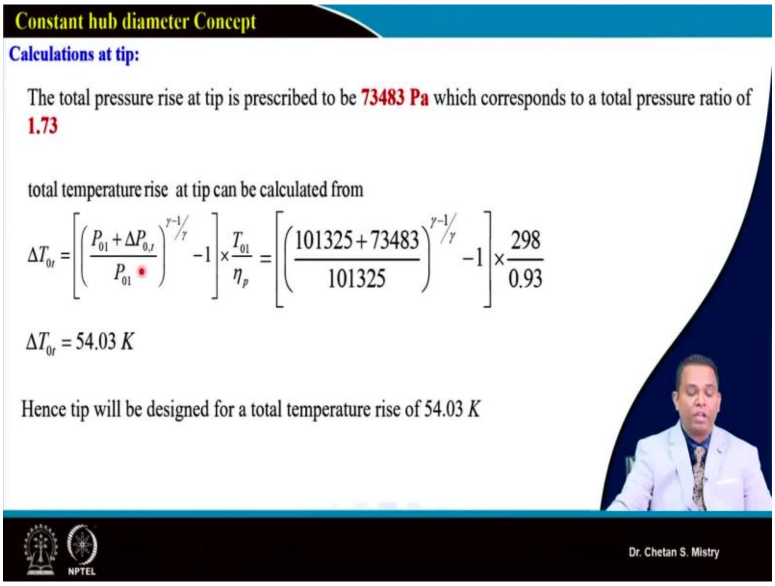

So, let us move forward. Say, here in this case, for say, tip station, as we have assumed our pressure ratio near the hub station to be 1.5 inline to that, let us assume our pressure ratio near the tip station to be 1.73. And if we are configuring this, that's what is giving me my ΔP_0 to be 73,483 Pa. So, if you are assuming this as a case, for tip station, we can calculate our ΔP_0 based on our fundamental equation. And that's what is coming 54.03 K.

$$\textit{The total pressure rise at tip is prescribed to be } 73483\ Pa$$

$$\textit{which corresponds to a total pressure ratio of } 1.73$$

$$\textit{Total temperature rise at tip can be calculated from}$$

$$\Delta T_{0t} = \left[\left(\frac{P_{01} + \Delta P_{0,t}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \times \frac{T_{01}}{\eta_p}$$

$$= \left[\left(\frac{101325 + 73483}{101325}\right)^{\frac{1.4-1}{1.4}} - 1\right] \times \frac{298}{0.93}$$

$$\Delta T_{0t} = 54.03\ K$$

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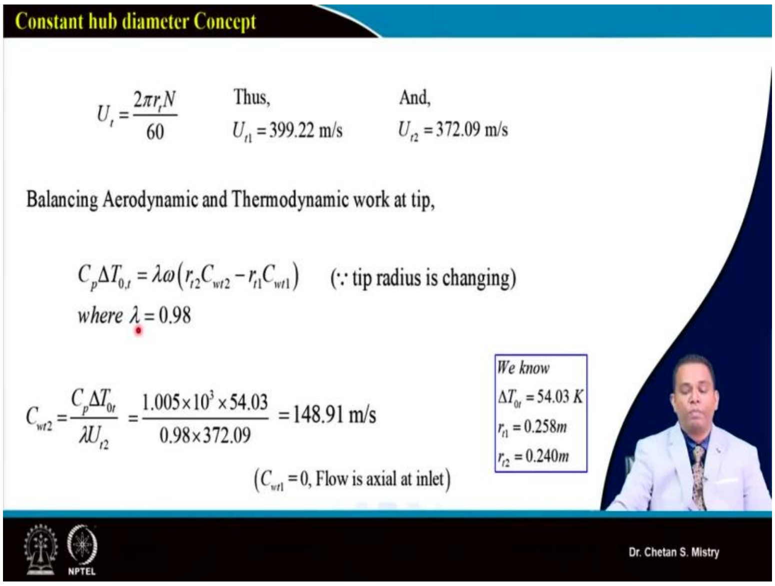

Now, based on calculation for our ΔT_0, we will be comparing our aerodynamic work and thermodynamic work that's what will be same. If we are configuring that case, we will be getting our swirl velocity component, that's what is say 148.91 m/s.

$$U_t = \frac{2\pi r_t N}{60}$$

$$Thus, U_{t1} = 399.22\ m/s$$

$$And, U_{t2} = 372.09\ m/s$$

$$Balancing\ Aerodynamic\ and\ Thermodynamic\ work\ at\ tip,$$

$$C_p \Delta T_{0,t} = \lambda\omega(r_{t2}C_{wt2} - r_{t1}C_{wt1})$$

$$where\ \lambda = 0.98$$

$$As\ C_{wt1} = 0\ (Flow\ is\ axial\ at\ inlet)$$

$$C_{wt2} = \frac{C_p \Delta T_{0t}}{\lambda U_{t2}} = \frac{1.005 \times 10^3 \times 54.03}{0.98 \times 372.09} = 148.91\ m/s$$

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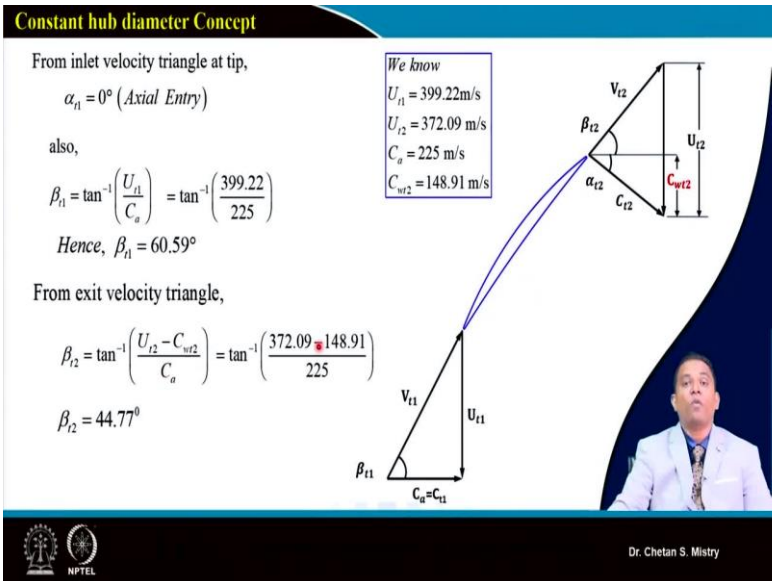

Now, once we know what is our whirl velocity component at the exit, we have assumed our entry to be axial, that means my C_{w1} at the tip, that's what is equal to 0. Based on our trigonometry, we can do our calculation for say, angle at entry as well as exit. So, we can say, my β_1, that's what is given by $\tan^{-1}(U/C_a)$. Since we know what is my tip diameter at the entry and axial velocity, that's what is giving me my β_1 as say 60.59°.

$$From\ inlet\ velocity\ triangle\ at\ tip,$$

$$\alpha_{t1} = 0° \ (Axial\ Entry)$$

$$also,$$

$$\beta_{t1} = \tan^{-1}\left(\frac{U_{t1}}{C_a}\right) = \tan^{-1}\left(\frac{399.22}{225}\right)$$

$$Hence, \ \ \beta_{t1} = 60.59°$$

Same way, at the exit we can write down that's what is say $\frac{U_2 - C_{w2}}{C_a}$. Since my C_{w2}, that's what we have calculated based on our comparison of work in sense of aerodynamics and thermodynamic work, we will be getting this C_{w2}, that's what is 148.91 m/s and that is giving β_2 to be 44.77°.

$$From\ exit\ velocity\ triangle,$$

$$\beta_{t2} = \tan^{-1}\left(\frac{U_{t2} - C_{wt2}}{C_a}\right) = \tan^{-1}\left(\frac{372.09 - 148.91}{225}\right) = 44.77°$$

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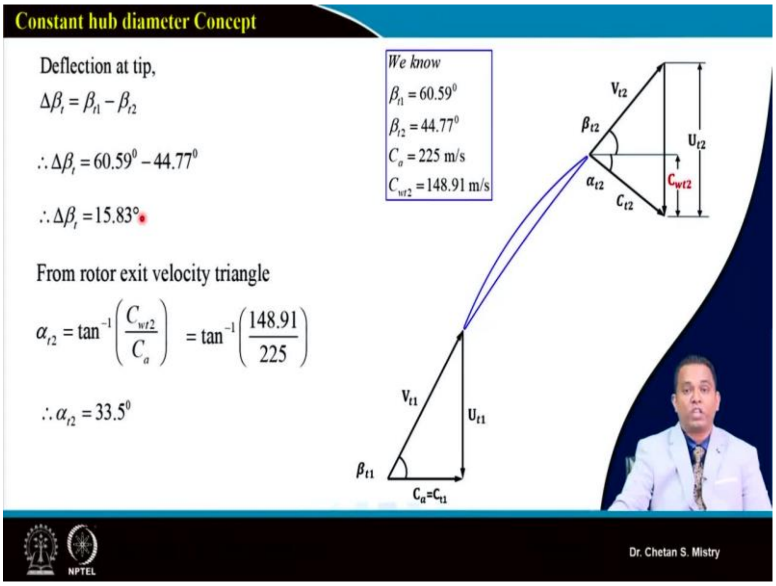

Now, once we have our β_1 *and* β_2 and, we can calculate our $\Delta\beta$ and that's what is coming 15.83°.

$$Deflection\ at\ tip,$$

$$\Delta\beta_t = \beta_{t1} - \beta_{t2}$$

$$\therefore \Delta\beta_t = 60.59° - 44.77°$$

$$\therefore \Delta\beta_t = 15.83°$$

So, next step for us it is to calculate what will be α_2, what will be other velocity components. So, if we are looking at exit velocity triangle, my α_2 that's what is coming as say C_w/C_a and that's what is coming 33.5°.

$$From\ rotor\ exit\ velocity\ triangle,$$

$$\alpha_{t2} = \tan^{-1}\left(\frac{C_{wt2}}{C_a}\right)$$

$$= \tan^{-1}\left(\frac{148.91}{225}\right)$$

$$= 33.5°$$

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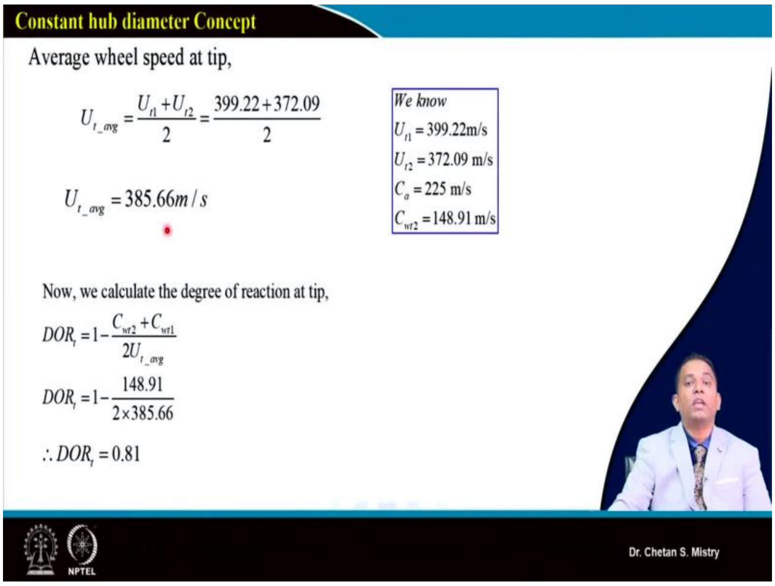

Now, we can do our calculation as we have done at mid station, we have done this calculation at the hub station and inline to that, we will be doing our calculation at the tip station. For our degree of reaction, we are looking for peripheral speed, that peripheral speed we are taking as say average peripheral speed and that's what is coming say 385.66 m/s. And if we are putting that number, degree of reaction at the tip that's what is coming 0.81.

Average wheel speed at tip,

$$U_{t_{avg}} = \frac{U_{t1} + U_{t2}}{2} = \frac{399.22 + 372.09}{2}$$

$$U_{t\_avg} = 385.66\, m/s$$

Now, we calculate the degree of reaction at tip,

$$DOR_t = 1 - \frac{C_{wt2} + C_{wt1}}{2U_{t\_avg}}$$

$$DOR_t = 1 - \frac{148.91}{2 \times 385.66}$$

$$\therefore DOR_t = 0.81$$

You can compare the numbers now. At hub, we are having say this degree of reaction it was coming 0.1 and at the tip we are having degree of reaction that's what is coming to be 0.81.

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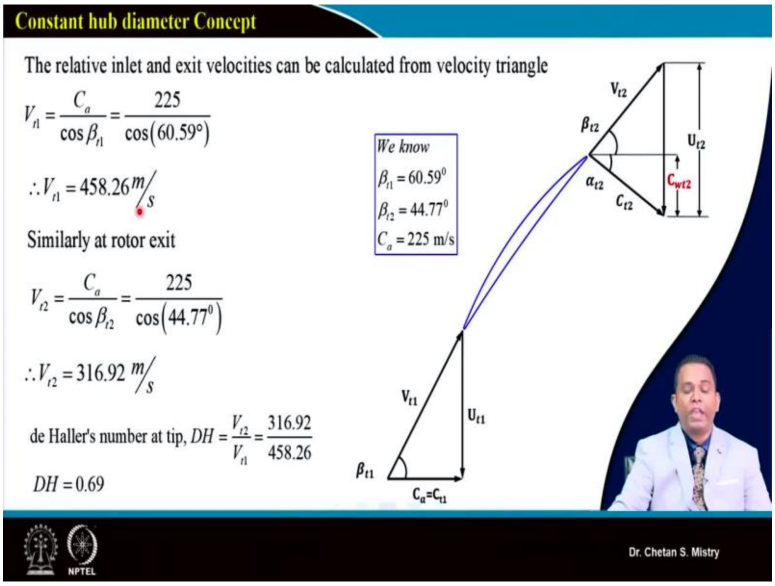

Now, based on our expectations for the calculation for relative velocity components at the entry, we can say that's what is given by C_a/V and this relative velocity component at the entry that's what is coming for 458.26 m/s. Similarly, at the exit, we can do our calculation and that's what is coming 316.92 m/s. So, based on that we can do our calculation for say de Haller's factor and that's what is coming 0.69.

$$The\ relative\ inlet\ and\ exit\ velocities\ can\ be\ calculated\ from\ velocity\ triangle,$$

$$V_{t1} = \frac{C_a}{\cos \beta_{t1}} = \frac{225}{\cos(60.59°)}$$

$$\therefore V_{t1} = 458.26\ m/s$$

$$Similarly\ at\ rotor\ exit,$$

$$V_{t2} = \frac{C_a}{\cos \beta_{t2}} = \frac{225}{\cos(44.77°)}$$

$$\therefore V_{t2} = 316.92\ m/s$$

$$de - Haller's\ number\ at\ tip,$$

$$DH = \frac{V_{t2}}{V_{t1}} = \frac{316.92}{458.26}$$

$$DH = 0.69$$

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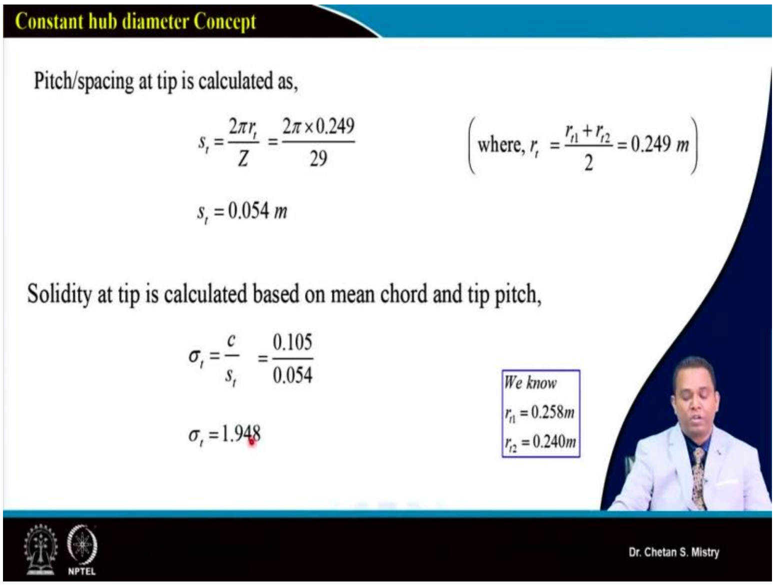

Now, as we have taken our number of blades to be 29. So, at the tip, we can do our calculation for pitch, we can do our calculation for the solidity and solidity near the tip based on chord to be say 0.105 m, the solidity is coming 1.948.

$$\textit{Pitch/spacing at tip is calculated as,}$$

$$s_t = \frac{2\pi r_t}{Z}$$

$$where, r_t = \frac{r_{t1} + r_{t2}}{2} = 0.249\ m$$

$$= \frac{2\pi \times 0.249}{29}$$

$$s_t = 0.054\ m$$

$$\textit{Solidity at tip is calculated based on mean chord and tip pitch,}$$

$$\sigma_t = \frac{c}{s_t} = \frac{0.105}{0.054} = 1.948$$

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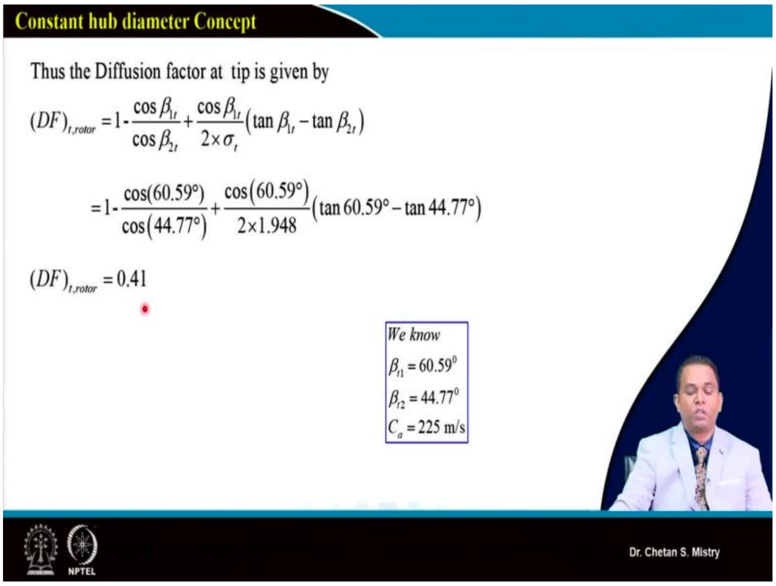

Now, once we have our solidity, we know what is our blade angles β_1 *and* β_2. We can do our calculation for diffusion factor at the tip and that's what is coming 0.41.

Thus the Diffusion factor at tip is given by,

$$(DF)_{t,rotor} = 1 - \frac{\cos\beta_{1t}}{\cos\beta_{2t}} + \frac{\cos\beta_{1t}}{2\times\sigma_t}(\tan\beta_{1t} - \tan\beta_{2t})$$

$$= 1 - \frac{\cos(60.59°)}{\cos(44.77°)} + \frac{\cos(60.59°)}{2\times 1.948}(\tan 60.59° - \tan 44.77°)$$

$$(DF)_{t,rotor} = 0.41$$

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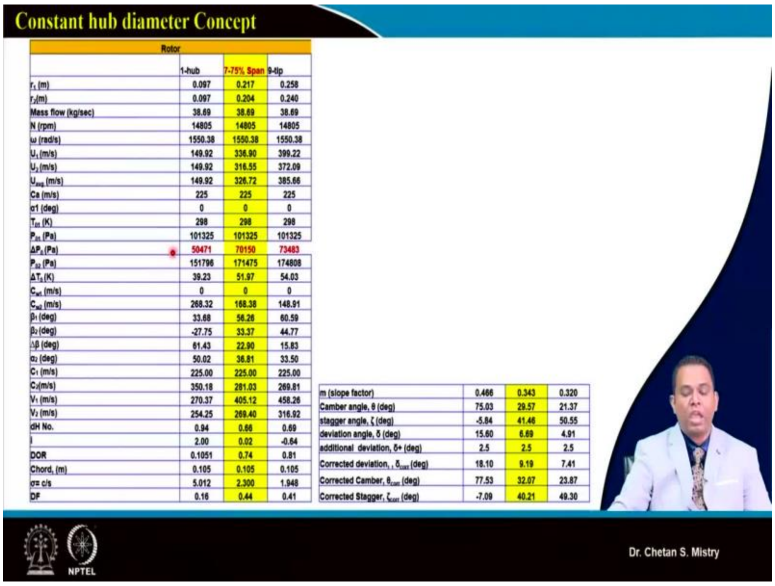

Now, these are the table. This is what is indicating the parameters at the hub station in line to that this is what is indicating what will be the parameters at our tip station, okay. And, these are the assumed values what we are discussing at this moment.

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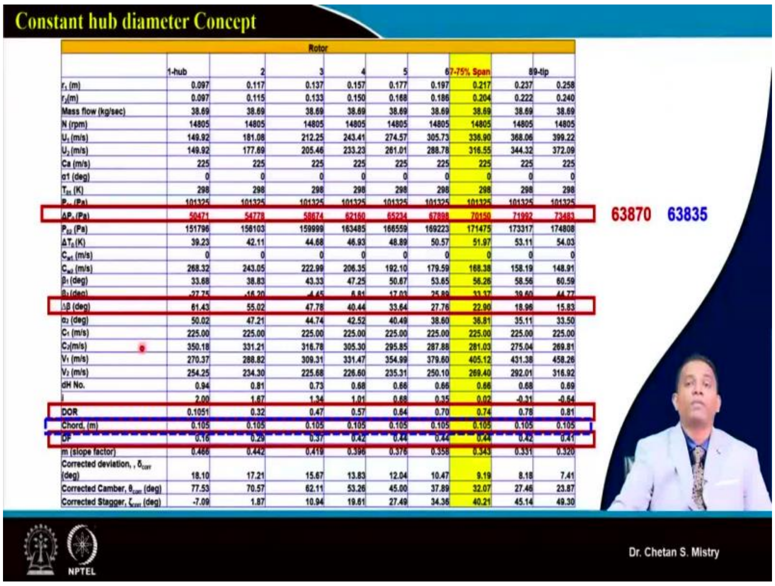

Now, based on this; now, we are having our numbers at hub, tip, we can extend that. So, whenever we are doing our design, let it be say subsonic compressor or let it be say supersonic or transonic compressor, what we will be doing? We will be initially doing calculation at 50% span for subsonic compressor, at 75% span for say transonic compressor.

Very first calculation we are doing at the mid station. Then immediately we will be doing our calculation at the hub station because that is where, suppose say if I am taking the approach of fundamental design configuration, we will be putting on our eye for different parameters. So, here if you look at, very first parameter I will try to look at that's what will be my $\Delta\beta$, next parameter we will be keep on eye, that's what is say degree of reaction. We will be putting our eye for say diffusion factor and next we will be putting our eye for say camber angle calculation.

Now, once this is what is giving the satisfaction, we will be doing our design for the tip station. Now, at hub, mid and tip station, once we have these numbers, that's what is known, what we need to do is we need to set this ΔP_0 throughout the span in such a way that my average total pressure that's what will be as per my expectation.

So, for here, we are expecting this pressure rise to be 1.63, that's what is expected ΔP_0 to be 63,835 Pa and that's what we are setting here, okay. Now, we are not having any configuration saying like what will be the tip clearance, suppose say this is what is known to you. So, accordingly you need to adjust your ΔP_0.

If you recall, when we were discussing say subsonic compressor design, that time we have configured like that considering say tip clearance to be say 3% or say 2%. Accordingly, you just adjust your ΔP_0 such that my pressure drop or loss that's what is happening near the tip region that will get compensated, okay.

Now, once this is what is configured with us, we know what is our C_2 what is our α_2. And, that's what will be the input for by further design for the stator. So, here in this case, since we have taken same configuration for aspect ratio for constant tip diameter configuration and constant hub diameter configuration, my chord that's what is coming to be on higher side, okay.

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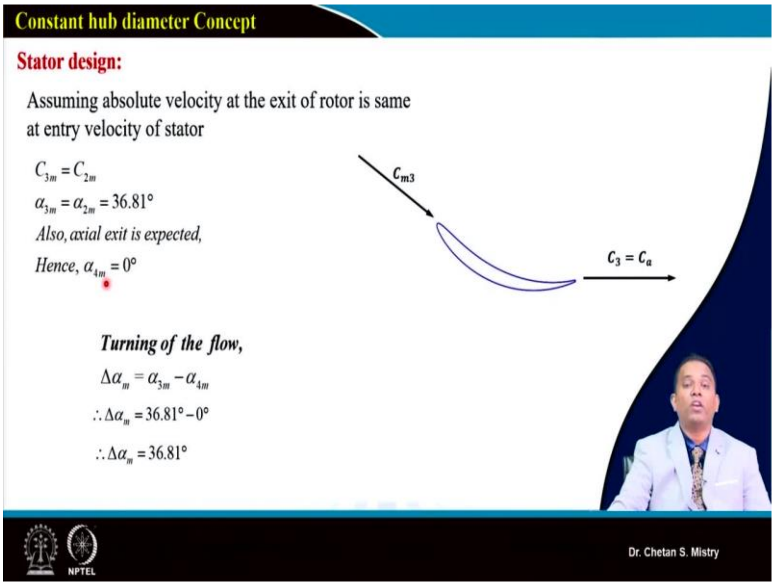

Now, let us say for the design of the stator. Say, if we configure as we discussed my $C_2 = C_3$ and $\alpha_2 = \alpha_3$, based on that we can do our calculation for $\Delta\alpha$. Now, since this compressor we are expecting our exit to be axial one, that is the reason my α we are putting say it to be 0.

Stator design:

Assuming absolute velocity at the exit of rotor is smae at entry velocity of stator

$$C_{3m} = C_{2m}$$

$$\alpha_{3m} = \alpha_{2m} = 36.81°$$

$$Also, axial\ exit\ is\ expected,$$

$$Hence, \alpha_{4m} = 0°$$

Turning of the flow,

$$\Delta\alpha_m = \alpha_{3m} - \alpha_{4m}$$

$$\therefore \Delta\alpha_m = 36.81° - 0°$$

$$\therefore \Delta\alpha_m = 36.81°$$

Here, we need to be very careful in sense of doing calculation for the stator. If we are going aggressively for the design of rotor, say aggressively in the sense if we are expecting our $\Delta\beta$ to be higher, then accordingly my turning required near the stator that also will be higher. If you recall we were discussing for say future design of compressor where we are looking for per stage pressure rise to be very high, under that configuration, this is what will be coming as a challenge.

There are chances that we will be having flow separation or stalling of blade that's what is happening for stator rather it will happen for rotor. So, this is what is it says it is easy to design in sense of stator rather it is very challenging and complex many times based on what loading you have selected for the rotor, okay. So, we need to be very careful when we are doing our calculation, rather going very aggressively towards a higher number, we need to keep on eye for many parameters, okay.

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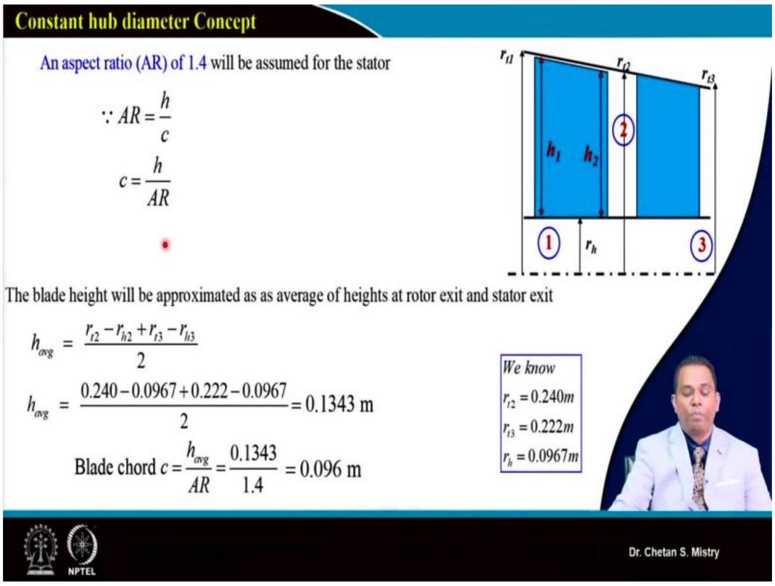

Now, here in this case, for the stator design, we have assumed our aspect ratio to be 1.4 for our earlier design. Same number we will be putting here, in order to do the calculation for say my height of the blade or the span of the blade, we are taking the average value and that's what is given by $\frac{h_2+h_3}{2}$, that's what we are writing here.

And if we are calculating that it says my height of the blade, that's what is coming 0.1343. And, here in this case, the chord for my stator is coming 0.096. If you recall when we have done our calculation for stator configuration for say constant tip diameter, under that configuration, my chord was coming 0.08. So, you can see what numbers we are selecting, that's what will be started reflecting in sense of the calculation. This is what is because of my change of the height and that height change, that's what is depending on which kind of configuration we are selecting with.

$$An\ aspect\ ratio\ (AR) of\ 1.4\ will\ be\ assumed\ for\ the\ stator$$

$$\because AR = \frac{h}{c}$$

$$chord\ of\ blade = \frac{h}{AR}$$

$$The\ blade\ height\ will\ be\ approximated\ as\ average\ of\ heights\ at\ rotor\ exit\ and\ stator\ exit$$

$$h_{avg} = \frac{r_{t2} - r_{h2} + r_{t3} - r_{h3}}{2}$$

$$h_{avg} = \frac{0.24 - 0.0967 + 0.222 - 0.0967}{2} = 0.1343m$$

$$Blade\ chord\ is\ thus, c = \frac{h_{avg}}{AR} = \frac{0.1343}{1.4} = 0.096\ m$$

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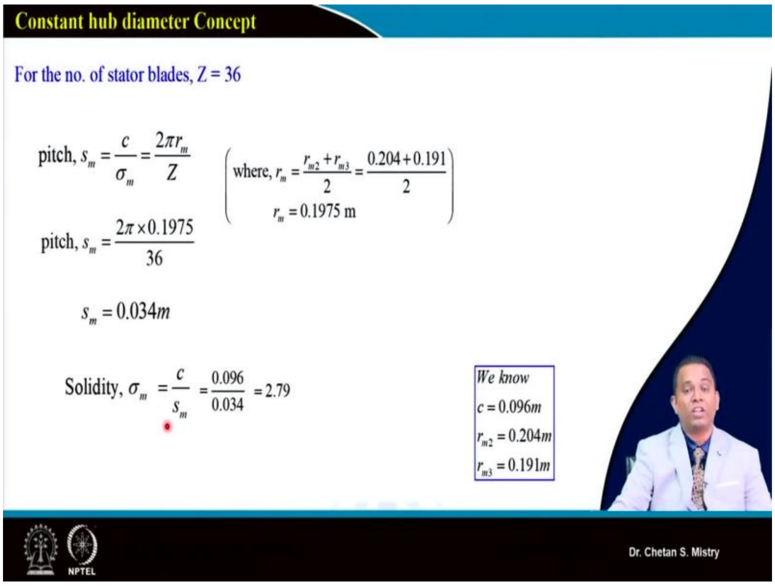

So, once we know what is our number of blades say for earlier design, we have taken our number of blades for the stator as say 36, the same number of blades we are configuring here. If we select that we will be having pitch as say 0.034 m and my solidity at the mid station is coming 2.79.

$$For\ the\ number\ of\ stator\ blades, Z = 36$$

$$Pitch, s_m = \frac{c}{\sigma_m} = \frac{2\pi r_m}{Z}$$

$$where, r_m = \frac{r_{m2} + r_{m3}}{2} = \frac{0.204 + 0.191}{2} = 0.1975\ m$$

$$Pitch, s_m = \frac{2\pi \times 0.1975}{36}$$

$$s_m = 0.034\ m$$

$$Solidity, \sigma_m = \frac{c}{s_m} = \frac{0.096}{0.034} = 2.79$$

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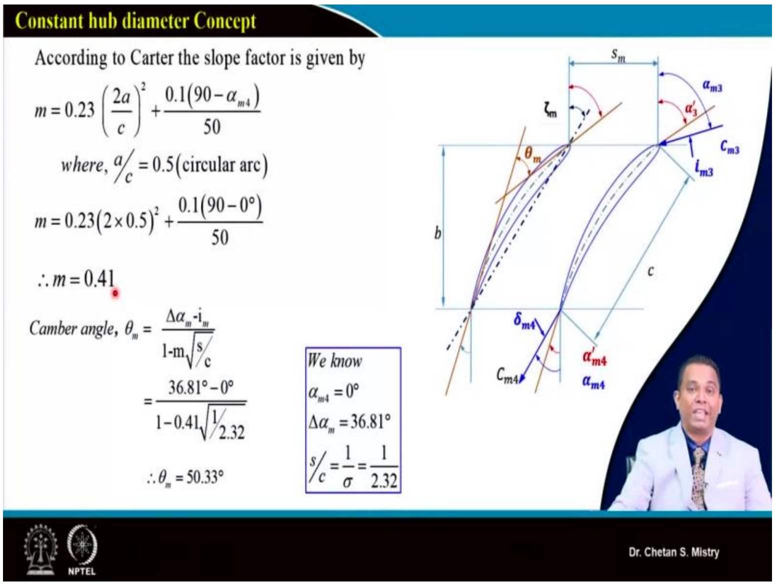

Now, we can calculate our say blade geometry or blade parameters, that's what is based on my Carter's m factor. So, that m factor we are considering here, that's what is coming 0.41. We can do our calculation for say camber angle based on the equation here in place of $\Delta\beta$, as we have discussed you need to configure $\Delta\alpha$ minus incidence. So, for incidence also we will be selecting at mid station incidence to be 0. And at tip station, we will be configuring that as say $-2°$ and at the hub station we will be taking that as say $+2°$. So, if you are putting that as a number, my angle…Camber angle that's what is coming 50.33°.

$$According\ to\ Carter\ the\ slope\ factor\ is\ given\ by$$

$$m = 0.23\left(\frac{2a}{c}\right)^2 + \frac{0.1(90-\alpha_{m4})}{50}$$

$$where, {}^{a}/_{c} = 0.5\ (circular\ arc)$$

$$m = 0.23(2 \times 0.5)^2 + \frac{0.1(90 - 0°)}{50}$$

$$\therefore m = 0.41$$

$$Camber\ angle, \theta_m = \frac{\Delta\alpha_m - i_m}{1 - 0.32\sqrt{1/_{2.32}}}$$

$$= \frac{36.81° - 0°}{1 - 0.41\sqrt{1/_{2.32}}} = 50.33°$$

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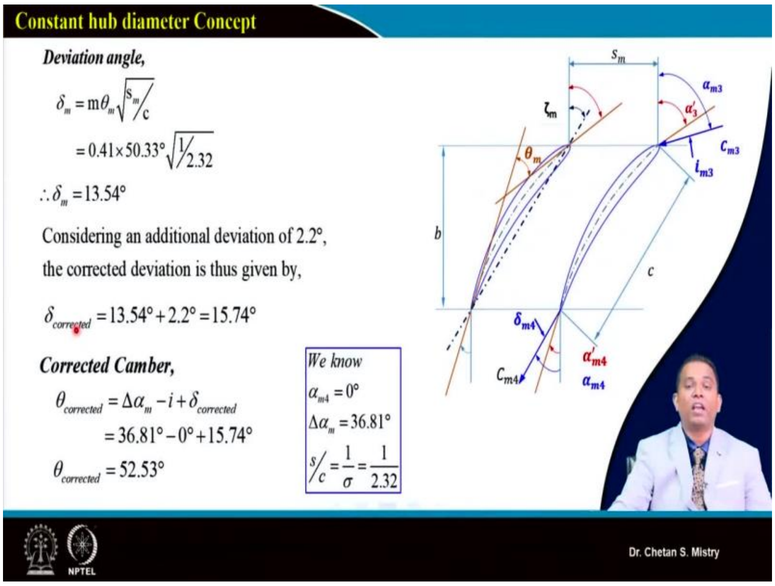

Now, we can calculate our deviation angle based on Carter's formula, and that’s what is coming say 13.54. As we have discussed, mainly based on your computational study you can make the correction in deviation angle. When you are making correction in deviation angle, accordingly your Camber and Stagger need to be modified. So, this is what is representing our modified say camber angle, that’s what is 52.53°.

$$Deviation\ angle, \delta_m = m\theta_m\sqrt{s_m/_c}$$

$$= 0.41 \times 50.33°\sqrt{1/_{2.32}} = 13.54°$$

$Considering\ an\ additional\ deviation\ of\ 2.2°, the\ corrected\ deviation\ is\ thus\ given\ by,$

$$\delta_{corrected} = 13.54° + 2.2° = 15.74°$$

$Corrected\ Camber,$

$$\theta_{corrected} = \Delta\alpha_m - i + \delta_{corrected}$$

$$= 36.81° - 0° + 15.74°$$

$$\theta_{corrected} = 52.53°$$

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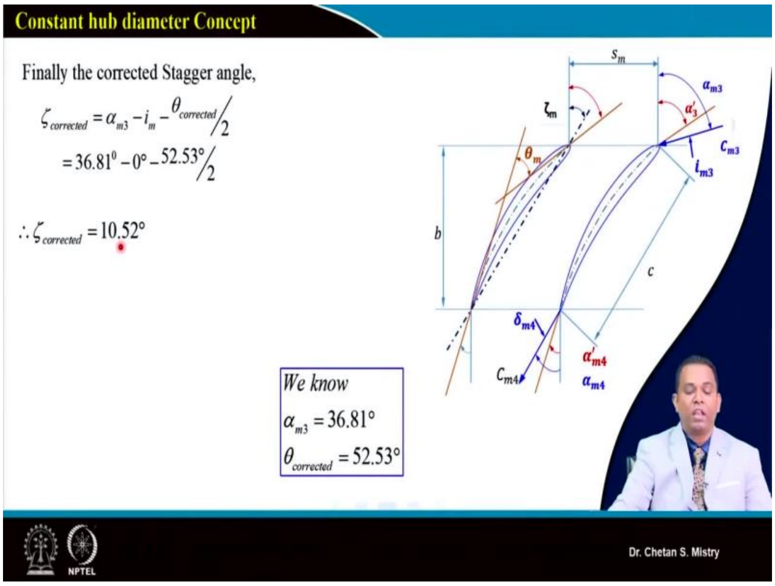

And, this is what is our stagger angle, that's what is coming as say 10.52.

$$Finally\ the\ corrected\ stagger\ angle,$$

$$\zeta_{corrected} = \alpha_{m3} - i_m - \theta_{corrected}/_2$$

$$= 36.81° - 0° - 52.53°/_2$$

$$\therefore \zeta_{corrected} = 10.52°$$

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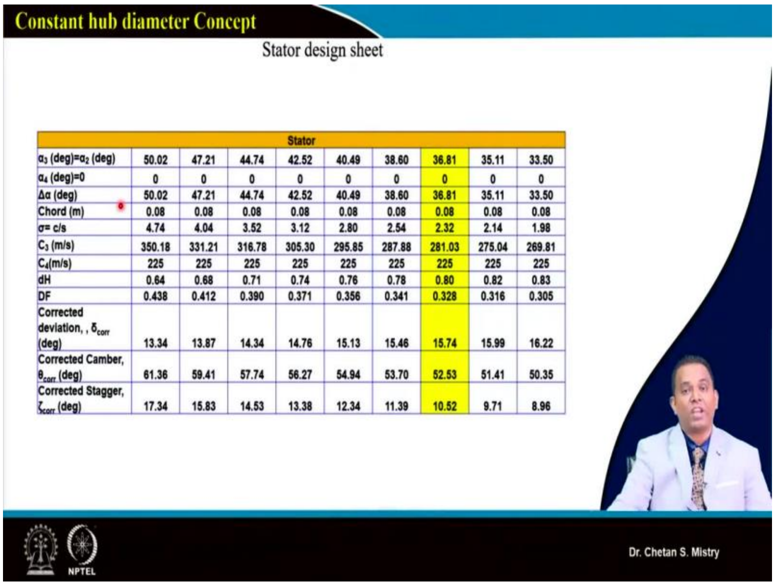

Stator									
α_3 (deg)=α_2 (deg)	50.02	47.21	44.74	42.52	40.49	38.60	36.81	35.11	33.50
α_4 (deg)=0	0	0	0	0	0	0	0	0	0
$\Delta\alpha$ (deg)	50.02	47.21	44.74	42.52	40.49	38.60	36.81	35.11	33.50
Chord (m)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
σ= c/s	4.74	4.04	3.52	3.12	2.80	2.54	2.32	2.14	1.98
C_3 (m/s)	350.18	331.21	316.78	305.30	295.85	287.88	281.03	275.04	269.81
C_4(m/s)	225	225	225	225	225	225	225	225	225
dH	0.64	0.68	0.71	0.74	0.76	0.78	0.80	0.82	0.83
DF	0.438	0.412	0.390	0.371	0.356	0.341	0.328	0.316	0.305
Corrected deviation, , δ_{corr} (deg)	13.34	13.87	14.34	14.76	15.13	15.46	15.74	15.99	16.22
Corrected Camber, θ_{corr} (deg)	61.36	59.41	57.74	56.27	54.94	53.70	52.53	51.41	50.35
Corrected Stagger, ζ_{corr} (deg)	17.34	15.83	14.53	13.38	12.34	11.39	10.52	9.71	8.96

Now, if you are putting this as in overall sense, this is what is representing our design for the stator. Now, for stator, if you are getting numbers to be different, say my $\Delta\alpha$ number, that's what is coming very high near the hub region, maybe that's what may give you indication that you need to change your loading accordingly. So, that you will not be having this great turning, okay.

So, always keep on eye when you are doing your design, okay. Suppose say, if you are doing your design in this way, then after later on when you will be doing your computational study, immediately, this is what will be reflecting in sense of maybe flow separation or flow three dimensionality, near the end wall region, specially near the hub region. And that's what will be reflecting you in sense of change of incidence angle, in sense of change of your deviation angle. And, that's what will be giving you indication that you need to modify your design.

So, again you need to go with the change in these parameters, then based on that you need to generate the new blades and again you need to do your iteration. So, in order to reduce the number of iteration at the preliminary design stage, what all we are doing at this moment, we need to keep on eye for all these parameters.

Otherwise, it may increase your number of iterations. Now, here this is what we are doing calculation for one of the stage. Now, we know, suppose if we consider say low bypass ratio engine, for that we will be having number of fans maybe one fan or maybe three fans, based on our design. So, accordingly, you may need to modify certain dimensions. So, when you are changing your dimension, again, you need to revisit this excel sheet program, modify those parameters, reiterate and again come up with final solution.

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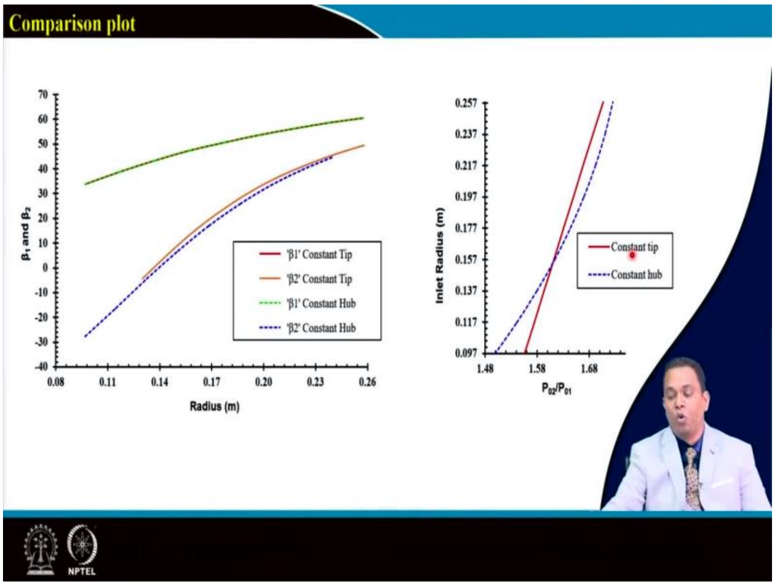

Now, this is what is representing the comparison between these two designs. Just look at, suppose if I consider this is what is we have taken. So, this is what is my inlet radius, do not get confused, because what we know my inlet radius, that's what is same. So, in order to compare the loading, I am taking say inlet radius as a reference.

So, here in this case, for constant tip diameter configuration, we were having our hub to be loaded on higher side, same way my tip, that's what has been loaded in a moderate way. Now, when we have done our second design, that's what is say constant hub diameter configuration, in that my hub is loaded low and at the same time my tip is loaded on the higher side.

Purposefully this kind of load configuration it has been selected with. So, do not get confused, we can consider same distribution of ΔP_0 both for constant hub diameter and constant tip diameter, but that's what will not serve the purpose for explaining this aerodynamic design. As a designer, we need to have all this kind of configuration to be in mind, okay.

So, maybe when you are doing your calculation, you can take these numbers for say constant tip diameter configuration, use this parameter of constant hub or maybe when you are doing your constant hub diameter configuration, you can do calculation using this ΔP_0, okay, and check.

So, now, you can understand, suppose say you are working in a firm where group of people they are doing or they are involved with the design and maybe in order to check with the design, it may be given that one of the group they will be working for constant tip configuration, one of the group that will be working on constant hub configuration.

Now, they all will be having different kinds of loading, or maybe they both will be selecting same loading; based on that performance assessment, that's what will be done. And finally, as per say our engine configuration, we need to be very careful, we are talking about design for single stage at this instant.

And we know, our compressor for aero engine or say our land-based power plant or say for process industry, that's what is made up of number of stages. It is a multi-stage axial flow compressor. And for that, maybe you need to go with number of design iterations, where your understanding, your expertise, that's what will be helping in order to reduce the number of iterations for the design.

Here, if you compare, this is what is representing my variation of β_1 *and* β_2. If you are configuring my β_1, that's what is same for both the cases, this is what is representing my variation of β_2, we need to be little careful here, say here if you look at, this is what is representing my constant hub diameter configuration. And this is what is representing my constant tip diameter configuration, okay.

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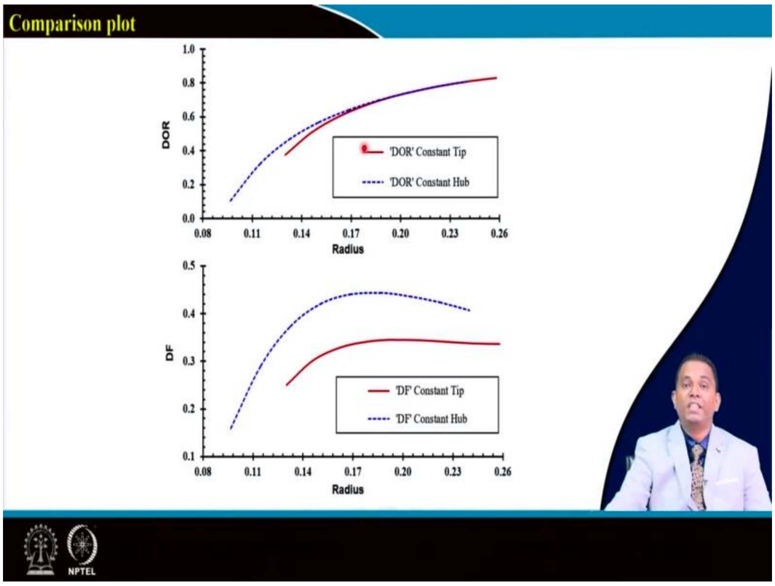

Now, what changes we have made, that's what will be reflecting in sense of say degree of reaction. So, here, this is what is representing the variation of degree of reaction for a constant hub configuration, as well as for constant tip configuration. If you configure, say for constant hub diameter configuration, my degree of reaction at the hub, that's what is going low.

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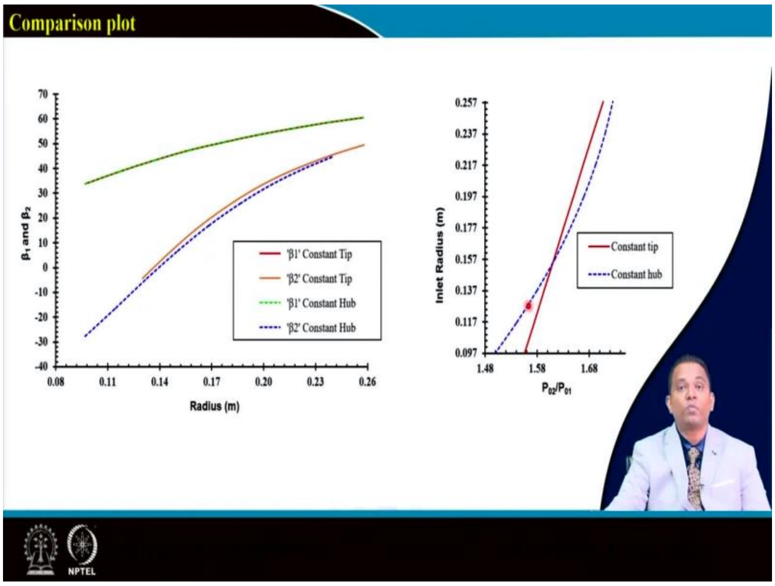

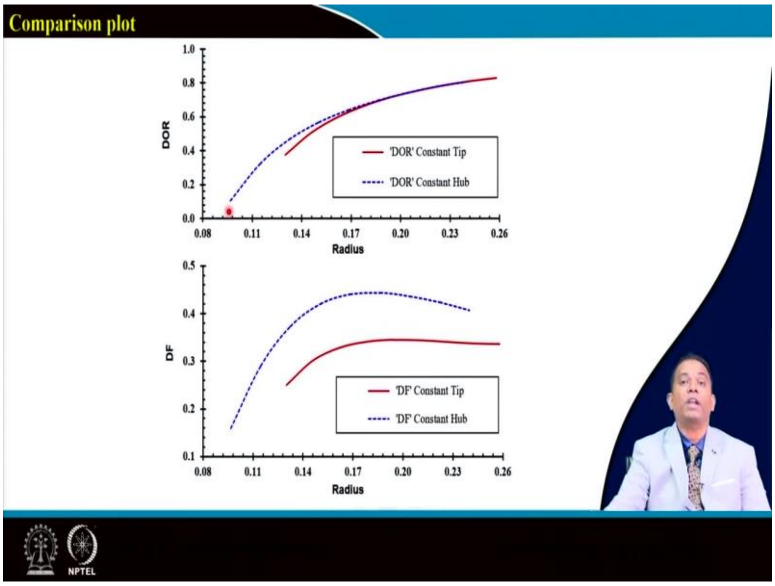

And, that's what we need to understand here, this is going low, because we are configuring our ΔP_0 expected pressure rise at the hub to be lower. It has nothing to do at this moment in sense of what design configuration you have selected with. This is what is because what ΔP_0 you are expecting, say for constant hub diameter, our expected pressure rise is say on a lower side. And, that is the reason why my degree of reaction number, that's what is coming to be lower, okay.

Suppose say, you are considering ΔP_0 to be different, it may give some different configuration. Same way, in order to compare this as say diffusion factor. We know our diffusion factor, that's what is a function of our solidity. And for solidity calculation, we have our chord as well as we have our number of blades, though we have selected our number of blades to be same, my chord, that's what was coming to be different. And that difference in sense of diffusive action, that's what is reflected here.

Again, this is what is a function of $\Delta\beta$ also. So, what loading you are selecting here, that's what is getting reflected in sense of change of diffusion factor. So, do not say configure this as say, you know, constant tip diameter design that's what is better than constant hub diameter configuration or constant hub diameter design.

This is what is all what numbers you are selecting with. Again and again I am saying same thing, you need to be little careful in sense of how ΔP_0 you are putting with. Suppose say, same design you will be doing with a free vortex configuration, maybe your variation will be different and it may be possible that your degree of reaction calculation near the hub region for both the configuration, say constant tip diameter and constant hub diameter, you will be having that's what is coming to be lower at the hub station. Your $\Delta\beta$ will be coming to be larger for free vortex concept, okay. And, this is what is advocating for moving with the fundamental design approach which will give you the great control in sense of what all you are expecting.

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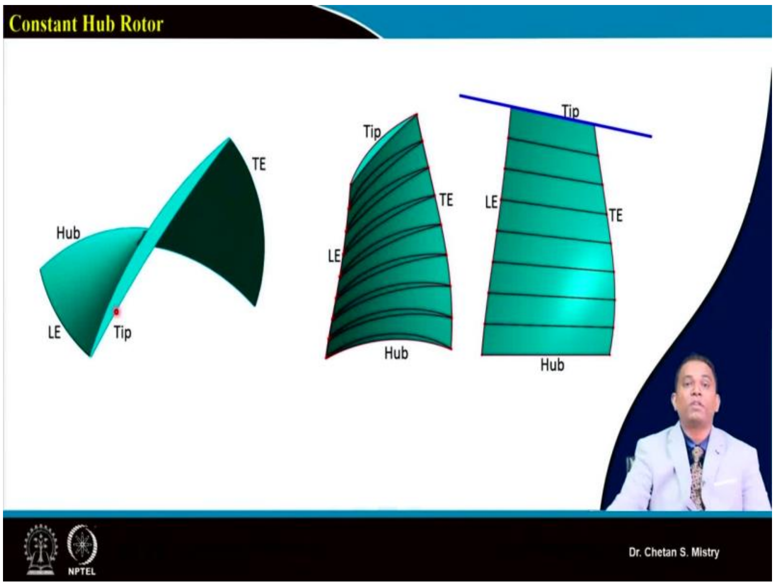

Let us try to look at what is the kind of blade we will be getting. So, this is what is representing when we are configuring our rotor to be constant hub diameter type. So, this is what is representing my hub station, my tip station, leading edge, trailing edge; same way, this is what is my transonic compressor, that is the reason why we have selected this as say DCA airfoil. And, here if you look at, this is what is representing how my blade angle that's what is varying all the way from hub to tip, okay.

There is a still scope, you can modify the loading near the hub and you can reduce this turning angle, okay. Now, this is what is representing my constant hub diameter configuration, this is what is representing my tip. Just understand one thing, this is not as we say like my chord is reducing. Chord is same, this is what is a view, okay. At the same time if you look at, these airfoil what you are looking at those airfoils are not 2D airfoils. We discussed this point when we were discussing about constant tip diameter kind of configuration. These airfoils are 3D airfoils. Because we are having our, say flow, that's what is getting deflected towards the hub region, okay.

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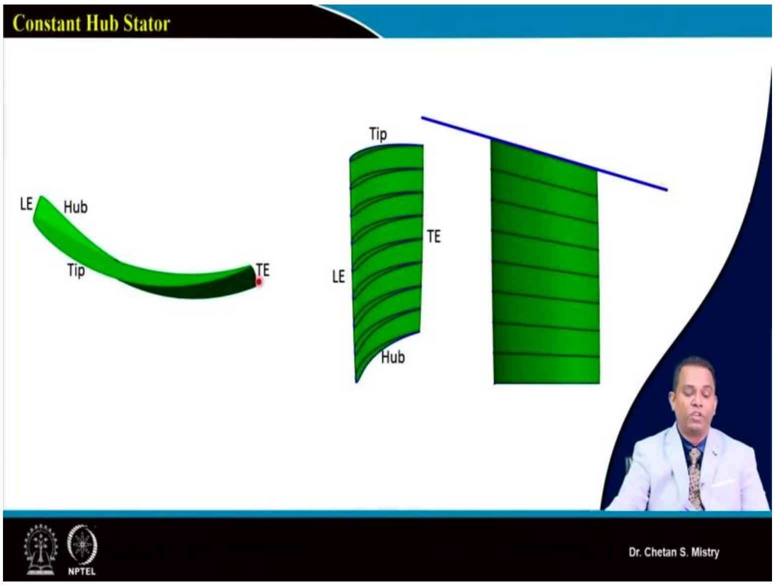

Let us do say, configuration for say stator, say for stator also. Now, my flow for the stator that's what is coming to be subsonic flow. And, that is the reason why we are selecting our blade as say C4. Or say airfoil of the blade, that's what is C4 airfoil. And that's what has been stacked about CG. So, this is what is representing how my angles, that's what is varying from hub to tip, and this is what is a view for constant hub diameter kind of configuration.

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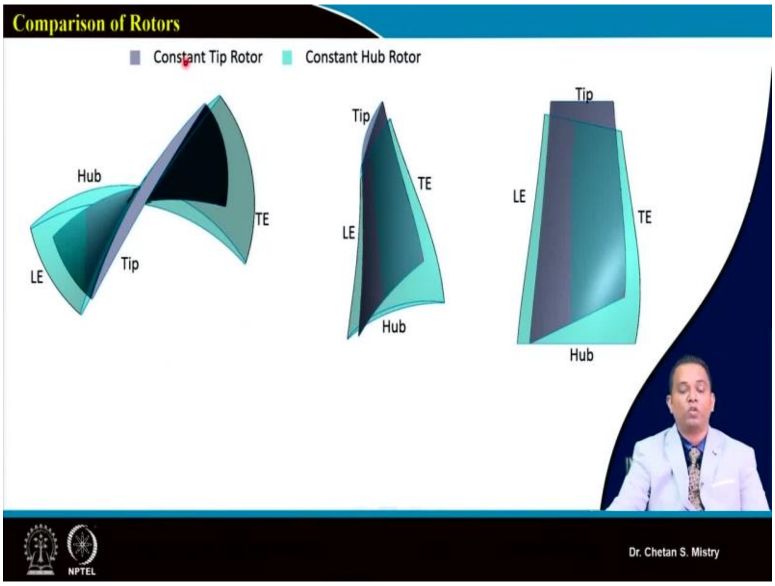

Now, this is what is very important, it is reflecting the comparison between these rotors. So, if you recall, when we were discussing the design, this is what is with the constant tip kind of rotor. And, second one, is transparent color, that's what is representing my constant hub kind of configuration. So, if we look at, as we have done our calculation, it says my chord for the rotor, that's what was coming to be larger, okay. And that's what is reflecting here. So, here you can see, this is what is a kind of rotor, that's what will be looking like, okay. So, this is what is with say constant tip kind of configuration, this is what is with say, constant hub kind of configuration.

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Same way, this is what is representing say, the stator configuration. Here if you look at, this is what is getting reflected in sense of constant hub kind of configuration for the stator. This is what is reflecting constant tip kind of configuration, you can see here. For that also, we have seen our chord that's what is coming to be slightly higher for say our constant hub diameter kind of configuration. At the same time, our angles are also different, okay.

Now, this is what will give you feeling of what all we are discussing. Again, it is very excited domain of doing work. And that to its design; design, that's what is very challenging, and very interesting. Once you will get involved, you will enjoy doing the design for both compressor as well as fans.

But as I told, you need to develop your own code, or you need to have your own design methodology. Now, you need to have your programming for development of airfoils. And, that's what you can make use of different equations, with different formulation, logic what all we have discussed in this course. I am sure, maybe in the near future, you all will be doing this kind of configurations, both for transonic as well as for subsonic kind of compressor as well as fans.

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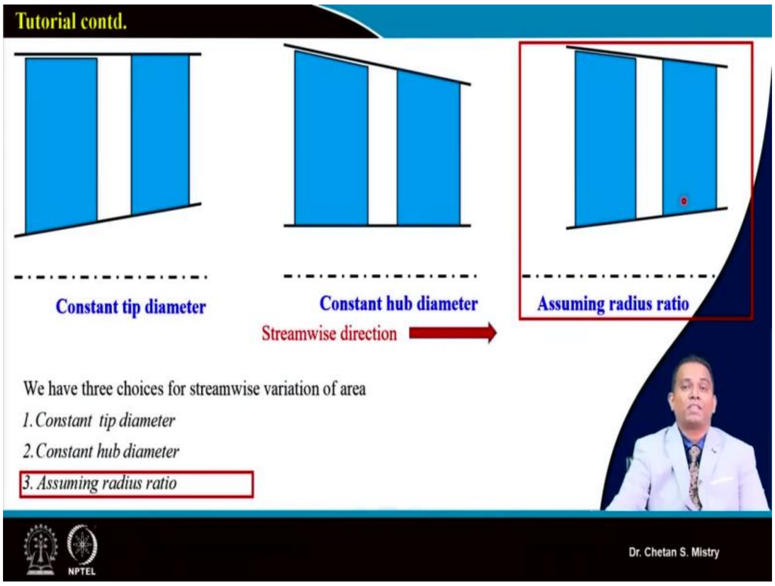

Now, here, this is what we were discussing about constant tip diameter configuration, constant hub diameter configuration; same way, we are having third logic, that's what is talking about say assuming radius ratio. So, we will not be discussing the design using this approach because, you know, that's what will be unnecessarily increasing the number of lectures and you also will feel little boring kind of situation. So, or to avoid that kind of situation, we will be discussing maybe you can try with your excel sheet program, maybe you can do your pen paper calculation using this kind of configuration.

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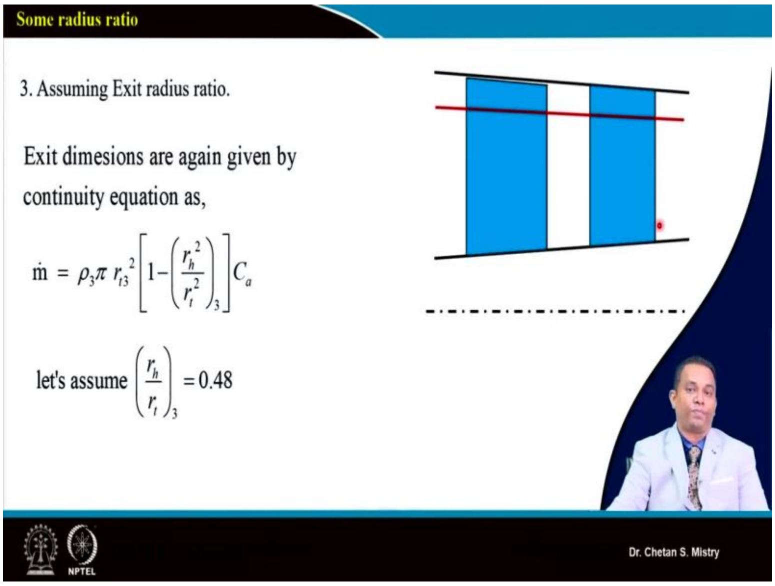

So, let us discuss about it says assuming the exit radius ratio. So, your entry radius ratio that's what is given to you, same way you can assume your exit radius ratio. Now, the question will come, say how we will decide this exit radius ratio? Suppose, if you are doing your design for say LP compressor last stage. Now, designer, they are doing their design for HP compressor situation is we will be having connection between LP compressor and HP compressor through say compressor duct, inter compressor duct.

Now, this aerodynamically this inter compressor duct that need to work absolutely fine with minimum losses and flow distortion. And, maybe possible the aerodynamicist who is doing that design, he will be going aggressively and he will say my entry or say exit of LP compressor will be having this dimension, okay.

Suppose say, that's what is your case. Same way, for HP compressor also, downstream we are having combustion chamber. So, the person who is doing design for combustion chamber, he will say this is what is the dimension I am expecting from last stage of HP compressor. So, under that condition, we will be having this kind of say radius ratio assumption we can go with.

Even you can go with constant mean diameter. So, if you recall, when we started discussing about say design of axial flow compressor, very first start we have done with the flow track, because that's what will be giving you idea what all we are discussing at this moment. So, just tried to brush up all we have discussed, what are the benefits of say constant tip diameter kind of flow track? What are the benefits of using constant hub diameter kind of flow track? What are the benefits of having say constant mean diameter kind of configuration? Or maybe you will be having, say some radius ratio configuration. So, here in this case, let us assume our radius ratio at the exit to be 0.48.

$$Exit\ dimensions\ are\ again\ given\ by\ continuity\ equation\ as,$$

$$\dot{m} = \rho_3 \pi r_{t3}^2 \left[1 - \left(\frac{r_h^2}{r_t^2}\right)_3\right] C_a$$

$$Let's\ assume\ \left(\frac{r_h}{r_t}\right)_3 = 0.48$$

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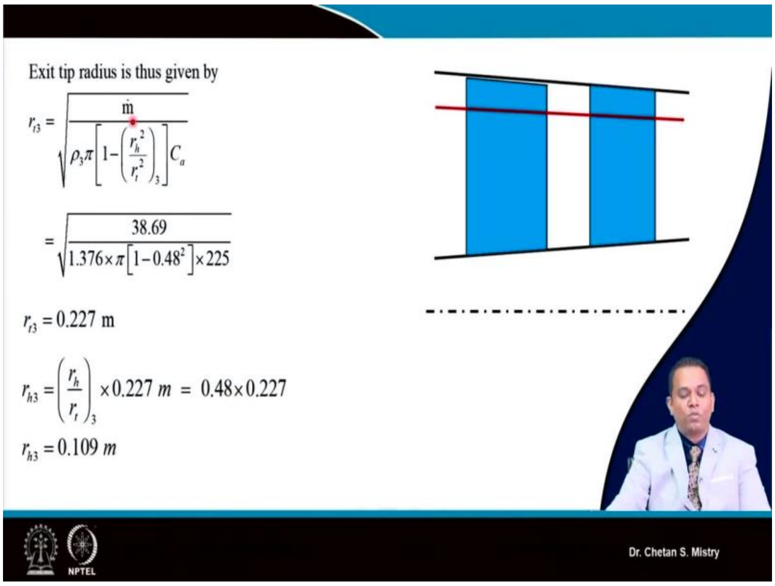

Now, if that's what is your case, all these numbers in sense of mass flow rate, my axial velocity, density everything that's what is known to us, that's what will be giving me my exit radius at the tip as say 0.227. And at the hub, that's what is coming as say 0.109, okay. So, when you are doing this design, you need to calculate your radius both at hub as well as at the tip, okay.

$$Exit\ tip\ radius\ is\ thus\ given\ by$$

$$r_{t3} = \sqrt{\frac{\dot{m}}{\rho_3 \pi \left[1 - \left(\frac{r_h^2}{r_t^2}\right)_3\right] C_a}}$$

$$= \sqrt{\frac{38.69}{1.376 \times \pi[1 - 0.48^2] \times 225}}$$

$$r_{t3} = 0.227\ m$$

$$r_{h3} = \left(\frac{r_h}{r_t}\right)_3 \times 0.227\ m = 0.48 \times 0.227$$

$$r_{h3} = 0.109\ m$$

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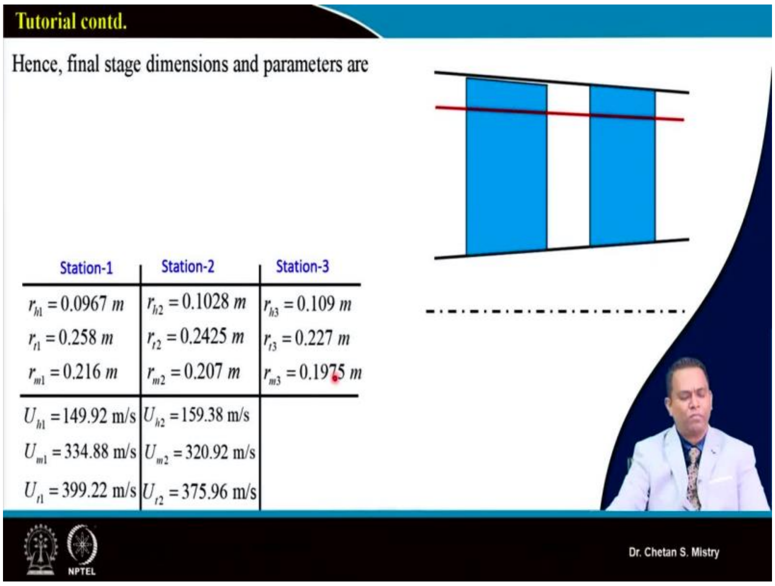

Now, if that's what is your case, these are the calculation for different stations; at station 1, station 2 and station 3.

Station-1	Station-2	Station-3
$r_{h1} = 0.0967\ m$	$r_{h2} = 0.1028\ m$	$r_{h3} = 0.109\ m$
$r_{t1} = 0.258\ m$	$r_{t2} = 0.2425\ m$	$r_{t3} = 0.227\ m$
$r_{m1} = 0.216\ m$	$r_{m2} = 0.207\ m$	$r_{m3} = 0.1975\ m$
$U_{h1} = 149.92\ m/s$	$U_{h2} = 159.38\ m/s$	
$U_{m1} = 334.88\ m/s$	$U_{m2} = 320.92\ m/s$	
$U_{t1} = 399.22\ m/s$	$U_{t2} = 375.96\ m/s$	

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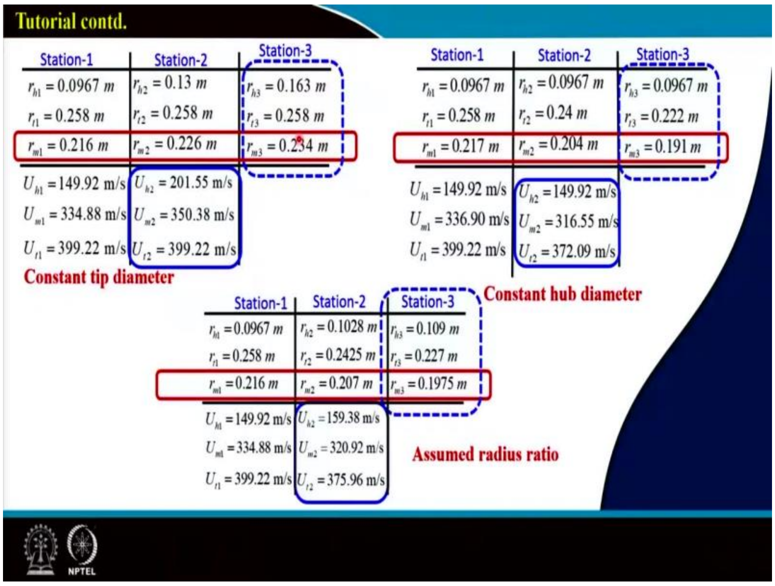

Now, let us compare. So, you know, this is what is overall scenario for the same compressor what we have designed using constant tip diameter configuration, designed with say constant hub diameter configuration and this is what is representing some assumed radius ratio, okay. Now, when we are comparing this is what is representing my mid station. So, if you try to compare this is what is indicating what is my, you know, change of mean radius. At the same time, we can compare in sense of what is happening at the exit. Now, this exit, that's what we say it is been maybe it is fixed by say next coming stage or maybe next coming duct, okay.

We are looking for some kind of management of flow; as we say, like we cannot be rigid or stubborn saying like no, I will be going with only this kind of configuration. Based on your requirement, maybe you need to go with modification in your design. And, that's what we are doing here. So, if you are comparing, say our hub radius, tip radius and mid radius, we can say my hub radius, that's what is coming slightly higher compared to your constant hub diameter configuration.

So, it may be possible when we are doing say constant hub kind of configuration, my problem for degree of reaction management, or my $\Delta\beta$ management, that's what is not happening, then it may lead to give you indication to move towards this kind of configuration. Just look at, this is what is in between kind of configuration.

Same way, the tip dimension, here, that's what is coming 0.227 and here this 0.22, this is what is 0.25, okay. So, here if we look at, the comparison for the peripheral speed, that's what is reflecting in sense of our $\Delta\beta$, in sense of my de-Haller's factor or diffusion factor, this is what all we need to take care of.

So, in overall, we can say, this is what will be giving you the idea of designing the transonic compressor with using three different approaches, okay. And with these all three different design approaches, I am sure, you will be able to do your design for a transonic compressor, let it be for say industrial compressor, let it be for aeroengine and let it be for say land based power plant.

Now, this is what is we have discussed in sense of designing using fundamental design approach. Now, it is always the case like looking to the aeroengine, people they are always excited looking to the blades for say fan. We have discussed earlier, these designers, they are going aggressively in sense of doing the design for the fans.

And, when we started discussing about the transonic compressor, that time also we were discussing about, say, different kind of whirl distribution that's what is possible for these transonic fans. So, we will try to discuss the transonic fan design in next lecture. So, thank you very much for your kind attention. And do your pen paper calculation. Make your excel sheet design program, that's what will be helping you to build the confidence. Thank you, thank you very much.