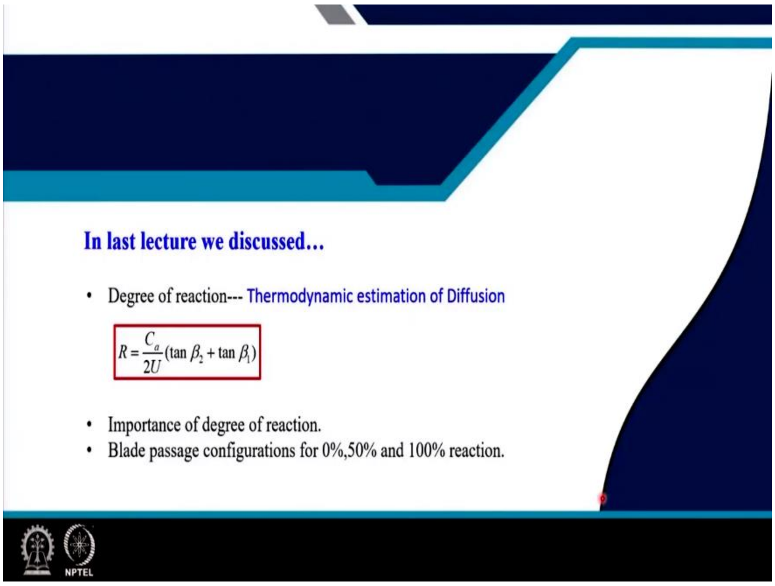
# Aerodynamic Design of Axial Flow Compressors & Fans

**Professor Chetankumar Sureshbhai Mistry**
**Department of Aerospace Engineering**
**Indian Institute of Technology, Kharagpur**

**Lecture 14**

## Stage Configurations and Parameters (Contd.)

(Refer Slide Time: 0:30)



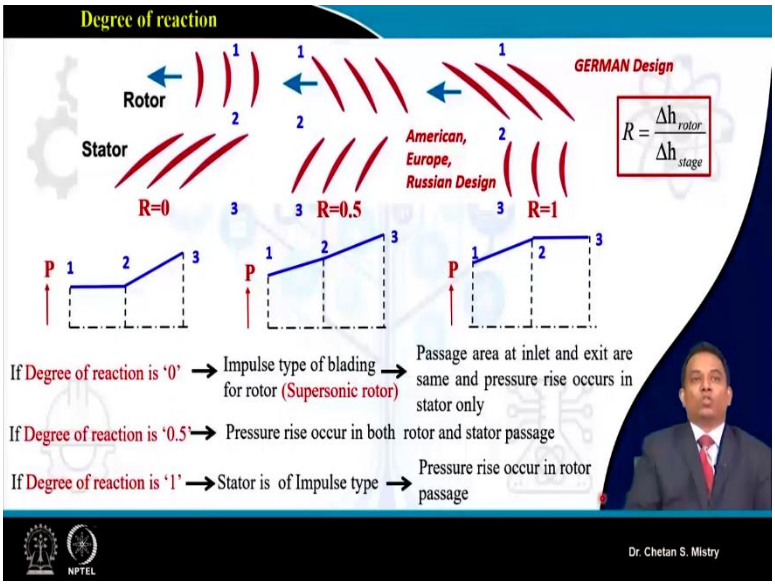

Hello, and welcome to lecture-14. In last lecture, we were discussing about degree of reaction, what we have defined as say static enthalpy rise in rotor divided by static enthalpy rise in our stage. We can say, this is what is a parameter which is representing our thermodynamic diffuser, okay. So, degree of reaction we can define as a thermodynamic estimation of our diffusion.

If you look at the equation for degree of reaction, that's what is representing, it is $C_a$ by 2U into bracket tan beta 2 plus tan beta 1.

$$R = \frac{C_a}{2U}(\tan\beta_2 + \tan\beta_1)$$

So, that's what is correlating our axial velocity, it is correlating our peripheral speed, it is also correlating our blade angles. So, you can realize what all are the importance of these parameters in design. Now, in order to understand the degree of reaction and its application, we have looked at three different configurations.

(Refer Slide Time: 1:36)



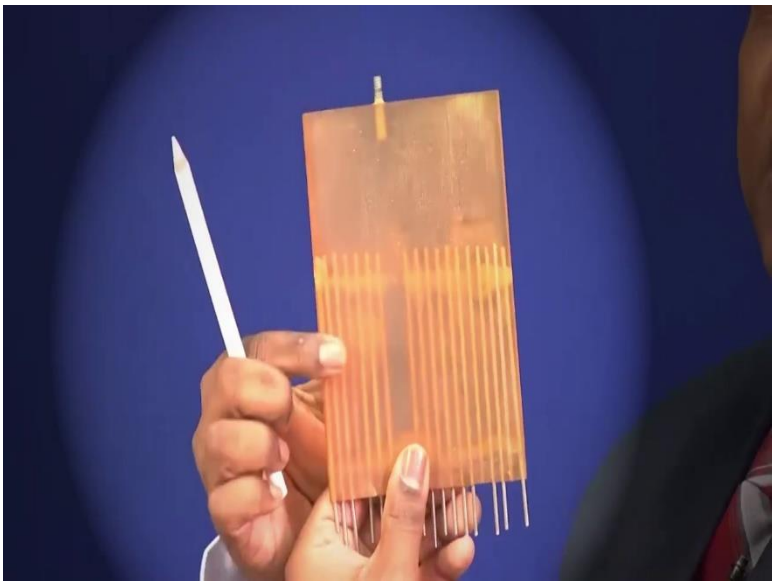

So, if you look at here, say we are having three different configurations in which we have taken degree of reaction to be 0, degree of reaction to be 0.5 or say 50% reaction, and degree of reaction to be 1 or we can 100% reaction. And in last lecture, we were discussing, when we are talking about say, 0-degree reaction that is representing there is no diffusion, that's what is happening in our rotor. The whole diffusion that is happening only in the stator. And that's the reason why we have our pressure rise only in stator.

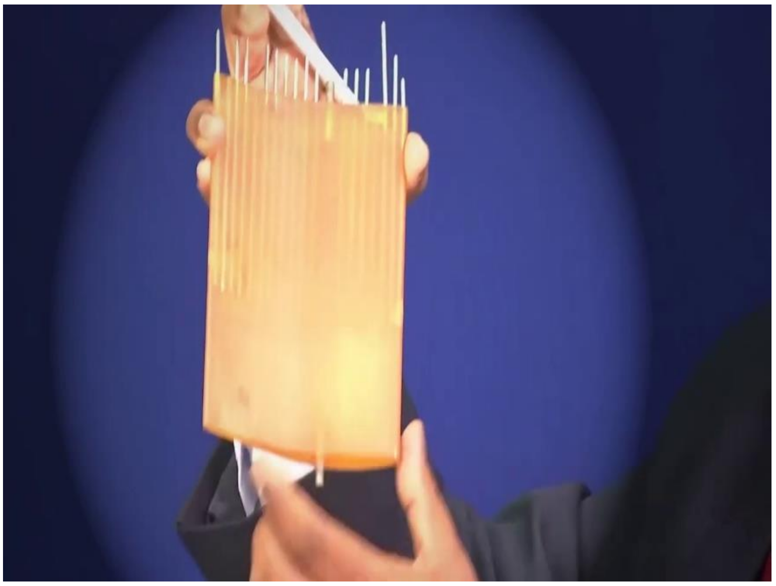
Now, when we have defined the degree of reaction to be 50%, it says my diffusion process that is distributed between rotor and stator. So, 50% diffusion, that's what is happening in our rotor, and 50% diffusion that is happening in our stator. For say 100% reaction, we have seen, we are having our whole diffusion, that's what is happening only in our say stator part, okay. So, in order to, say for 100% reaction, our diffusion, that's what is happening only in rotor.

Now, we have discussed there are different design strategies, design methodology, that's what has been adopted say throughout the world. For most of the German designs, that's what is with 100% reaction or near 100% reaction; most of the Americans, Europeans and Russian designs are for 50% reaction. So, here if you look at this process, or this passage, that's what is happening between the blade, that's what is required a special kind of airfoils. And we have discussed in one of the lecture, there are different kinds of airfoils we are using for say subsonic process and for transonic process.

So, let me show you different kinds of airfoils. Before going into the detail, let us look at here, suppose if I consider, say I am having my rotor to be a constant area passage, so you can understand I need to manage my airfoil in such a way that it will give constant area passage. Same way, if I am looking at 100% reaction, I need to make my blade passage for rotor in such a way that it will be giving me diffusing passage and my stator that will be giving constant area passage. So, whole this passage development as we have learned that need to be managed by our airfoils. So, let me show you some of the airfoil and some of the blades which are available with us.

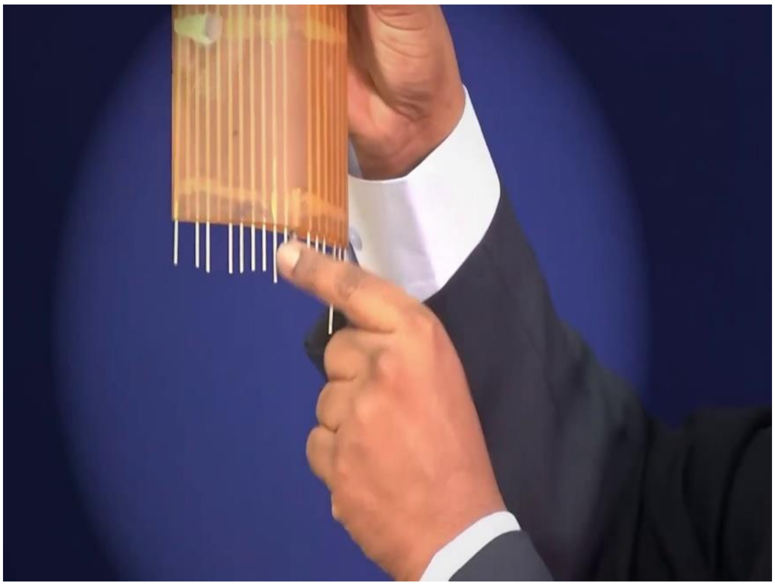
(Refer Slide Time: 4:26)

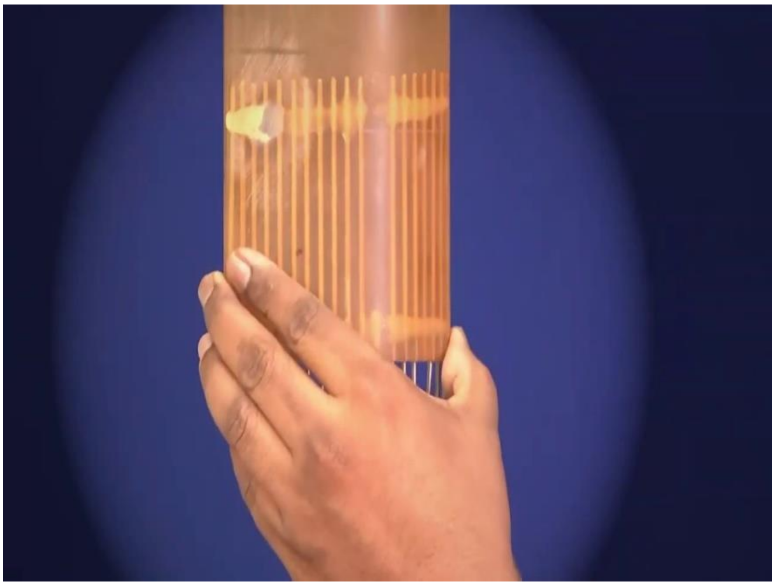




So here, this is what is one of the Cascade, Cascade for axial flow compressor blade. Say, this is what is one of the airfoil section, at say mid-section of my blade. If you look at here, this is what is my leading edge, this is my trailing edge, you can understand now this is what is my pressure surface, this surface is my suction surface. So, cascade as we have learned, this is what is say having section throughout the span to be same, okay.

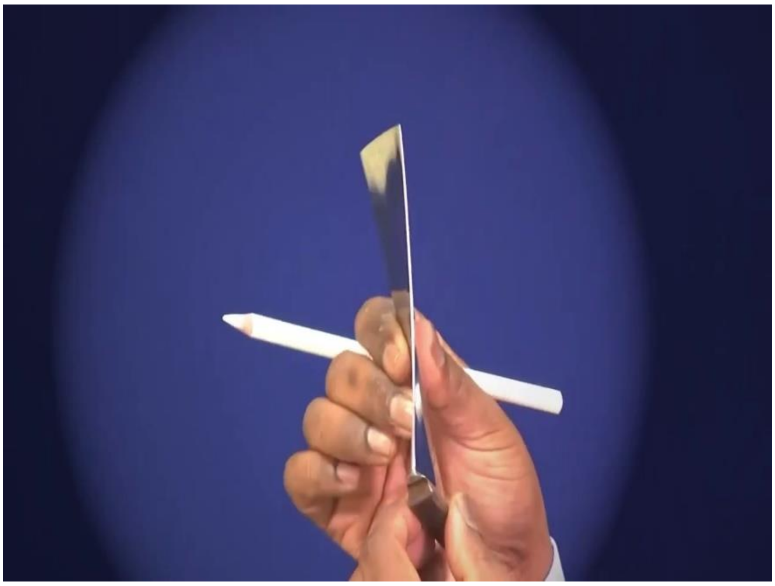
(Refer Slide Time: 5:04)





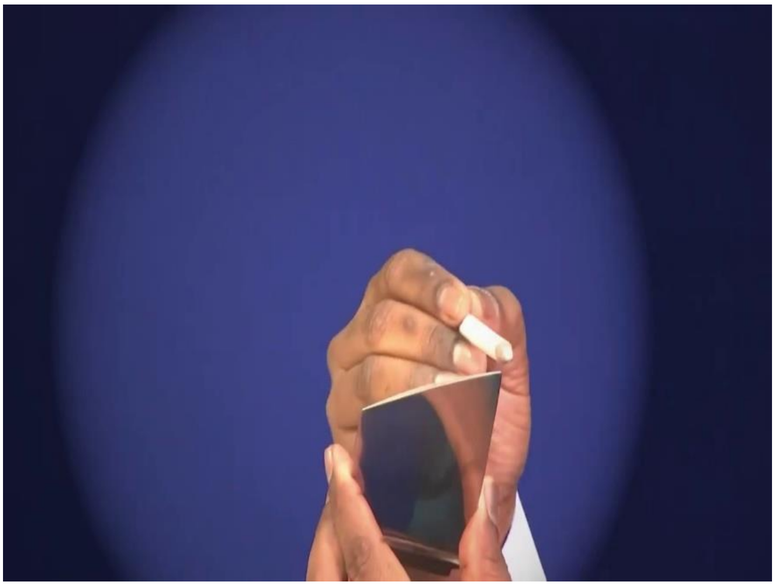
So, here if you look at carefully, this is what is in line to what we have seen in sense of our airfoil that’s what is say CDA kind of airfoil that is ‘Controlled Diffusion Airfoil’. Now, in order to estimate the $C_P$ distribution, we are having different tappings here. So, if you can look at, there are 0.2 mm different tappings that’s what has been done on the surface at the mid-section and they are been connected with these tubes. These tubes that will be connected with the pressure scanner in order to measure the $C_P$ distribution on pressure surface as well as on say suction surface. So, this is what is one kind of say… cascade.

(Refer Slide Time: 5:51)

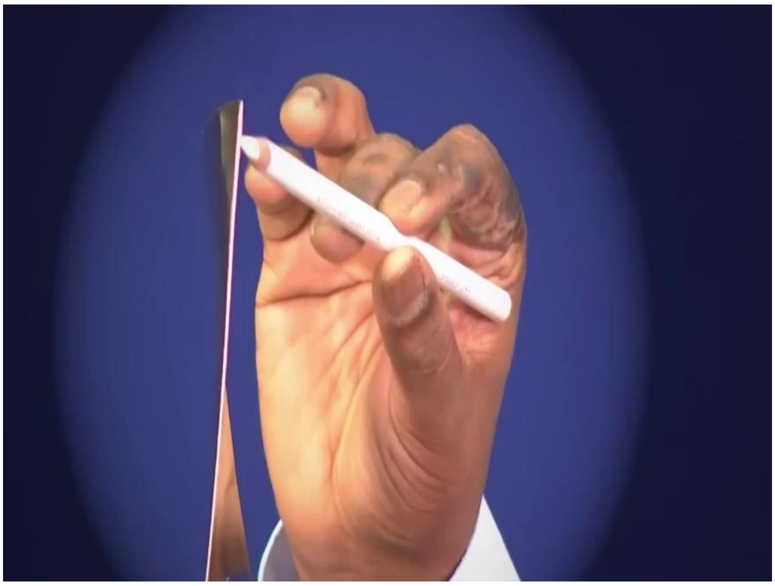


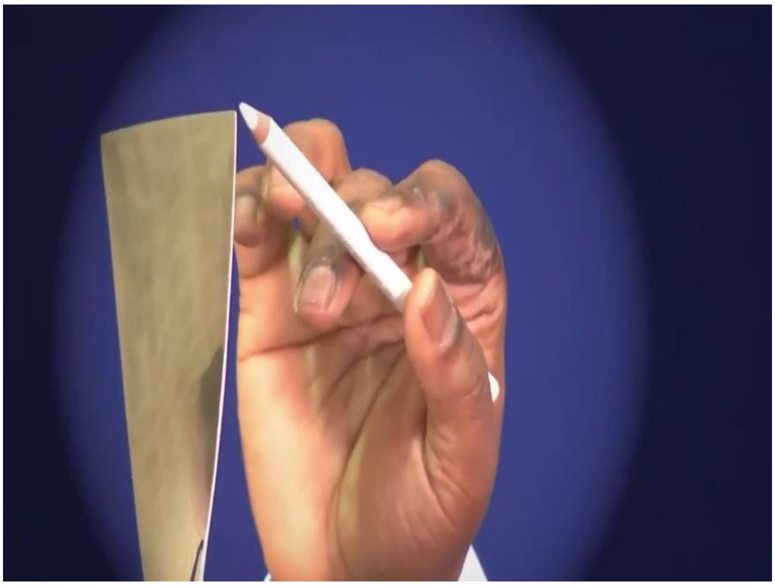
Now, let me show you, say this is what is one of the blade for say LP fan, okay. Now, if you look at carefully I was talking to you in sense of change of area. So, if you look at carefully, say this is what is my entry and this is what is my exit. So, if you look at carefully, this is what we defined as a leading edge and this edge, that’s what is defined as a trailing edge.

(Refer Slide Time: 6:22)



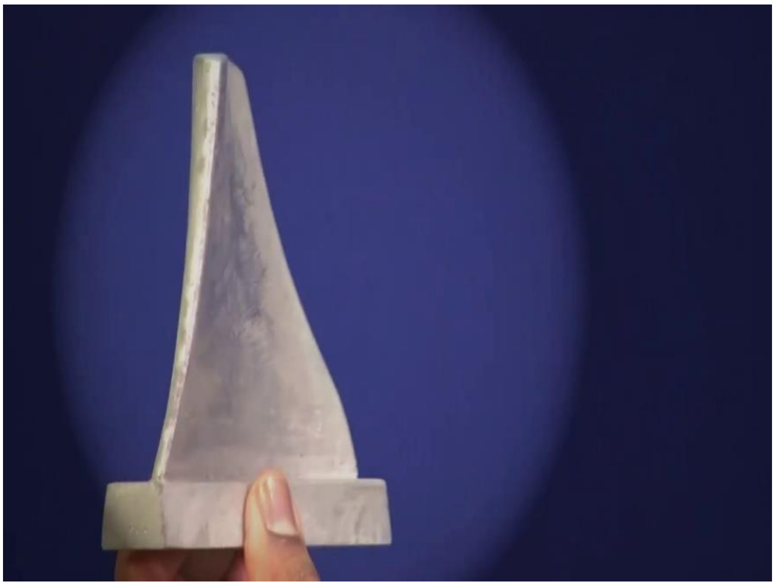


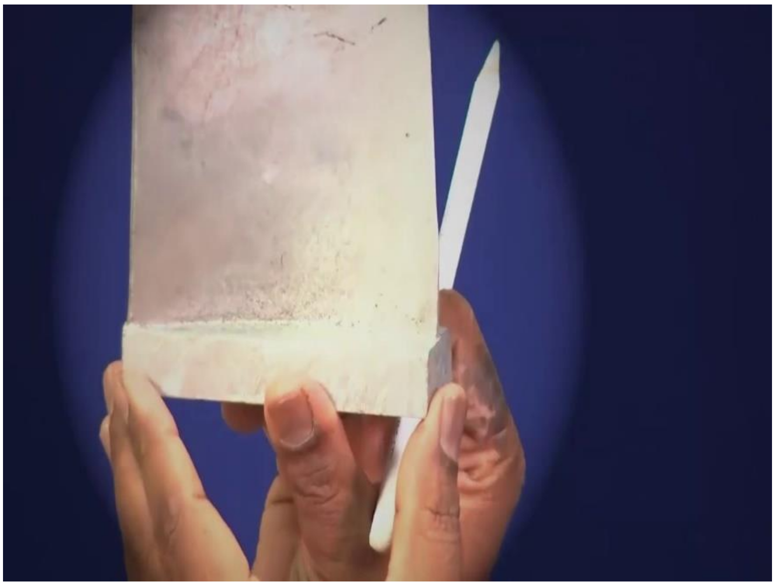


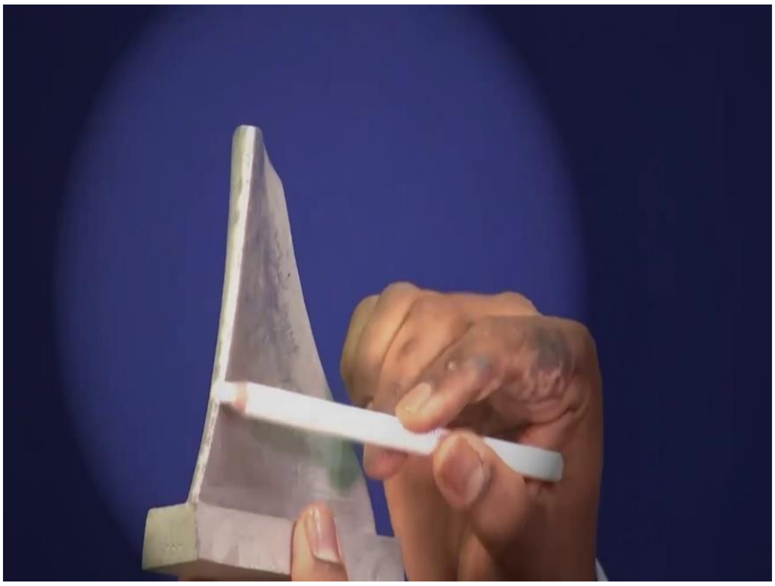


Now, for this blade; so, if you look at here, this is what is having say different kind of pressures surface and suction surface. So, this blade it is a transonic blade for LP compressor or say LP fan and this is what is having thickness to be less and if you look at this is having say ‘Double Circular Arc’. So, you can say this is what is my first circular arc, this is what is my second circular arc and if you look at carefully near the hub region, we are having our blade shape to be different and it is having the leading edge thickness to be different. And if we are moving towards the upside, near the tip region, we will be having this leading edge to be sharp as well as our trailing edge also will be sharp.

(Refer Slide Time: 7:10)

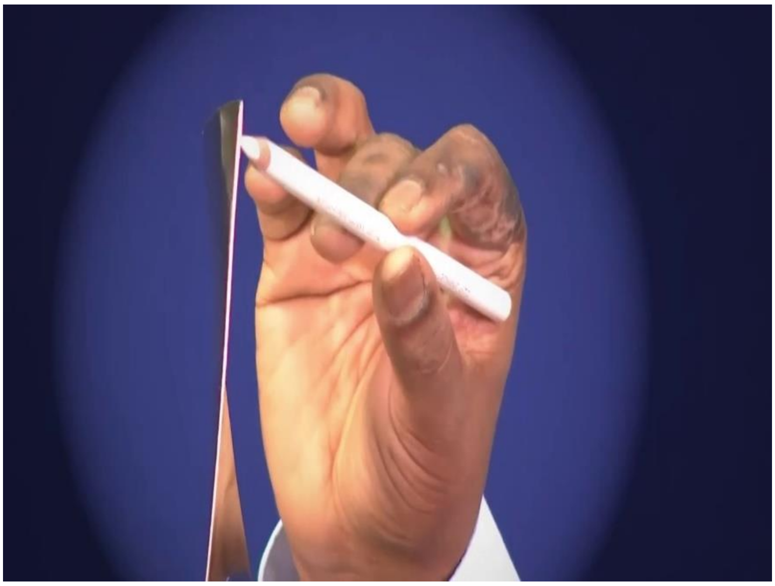






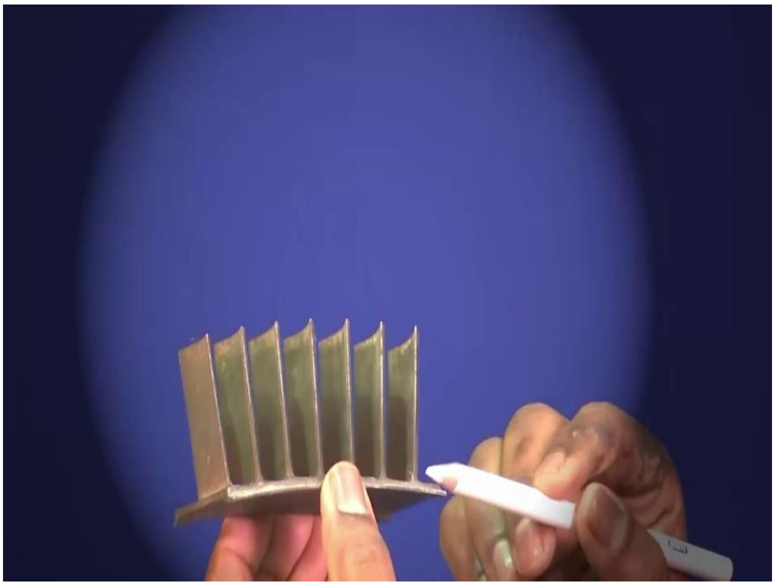
Now, say this is what is one of the blade for low speed application for say university research. If you look at carefully, this is what you can say, it is a highly twisted blade. Here we are having this as our suction surface, this is what is our pressure surface. You can see, we are having say leading edge, we have our trailing edge and if I show, say this blade that’s what is having C4 airfoil, okay.

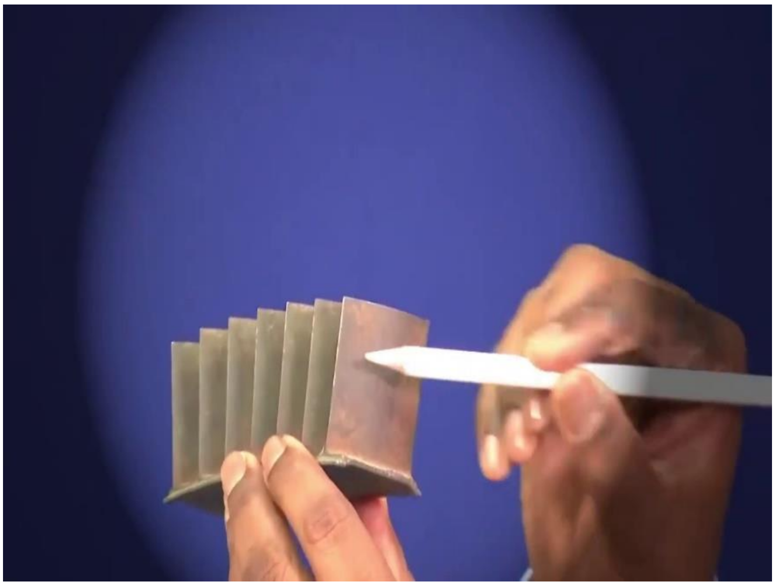
(Refer Slide Time: 7:46)



And throughout the span this airfoil, that’s what is remains same. And if you look at carefully, this blade is highly twisted blade. We will be discussing what is the reason why it is like that, but at this moment, in order to realize, you can see we are having C4 kind of airfoil and this all airfoil at different stations…. at different stations, they are being stacked about the CG point, CG that’s what is placed somewhere here.

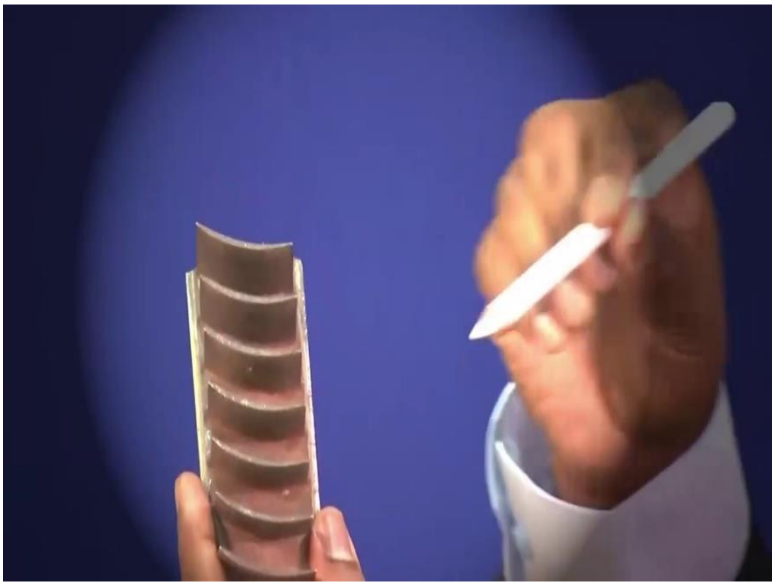
(Refer Slide Time: 8:18)





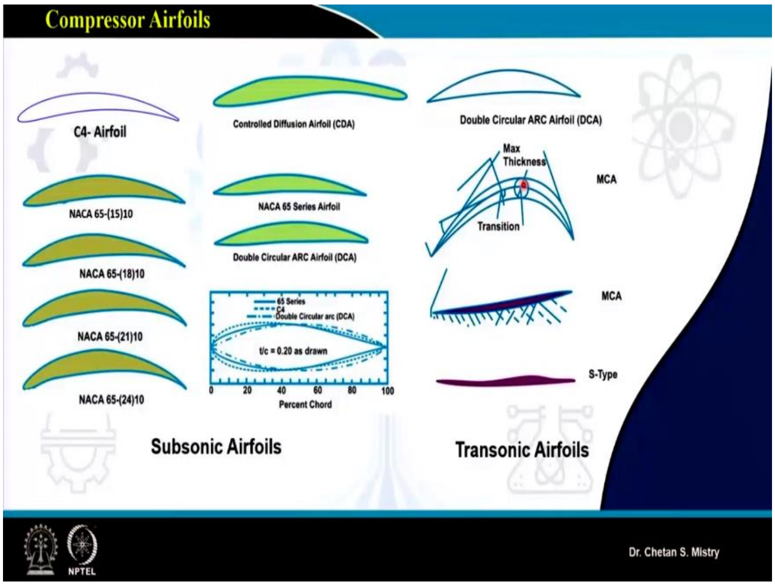
Now, let me show you, say this is what is one of the HP compressor blade and if you look at carefully, there are more number of blades for the HP compressor and that's what is having say aspect ratio to be nearly 1. So, the span of my blade and chord of my blade, that's what is approximately 1.

(Refer Slide Time: 8:43)



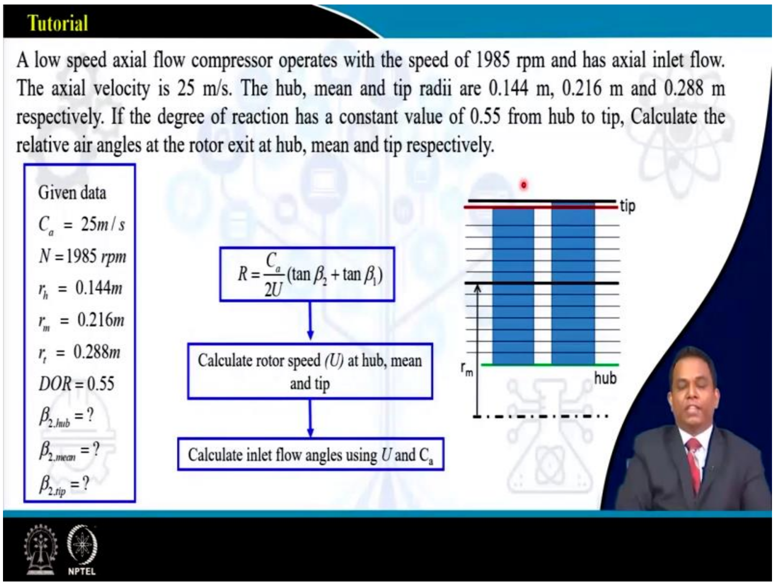
And if you look at carefully, in construction, say here we are having the leading edge, this is what is my trailing edge and you can see, this is what is the thickness distribution between this say suction surface as well as pressure surface. And this passage, if you consider, you will be having say entry area to be smaller your exit area to be say larger. And if you recall, we were discussing this airfoils are of say subsonic kind, okay. So, this is not exactly C4 airfoil or NACA 65 airfoil, that's what is been made by the engine manufacturing company.

(Refer Slide Time: 9:23)




With this background, I am sure, you are able to understand what all are the different kinds of blades and what all are the different kinds of cascades, okay. Now, with this background, let us try to understand one of the numerical for calculation of degree of reaction that will be giving you more clarity in sense of understanding for calculation.

(Refer Slide Time: 9:50)




So, let us see, this as one of the numerical. So, it says, a low speed axial flow compressor operates with the speed of 1985 RPM and has axial inlet flow. The axial velocity is 25 $m/s$. The hub, mean and tip radius are 0.144 m, 0.216 m and 0.288 m, respectively. If the degree of reaction has a constant value of 0.55 from hub to tip, calculate the relative air angles at the rotor exit at hub, mean and tip respectively.

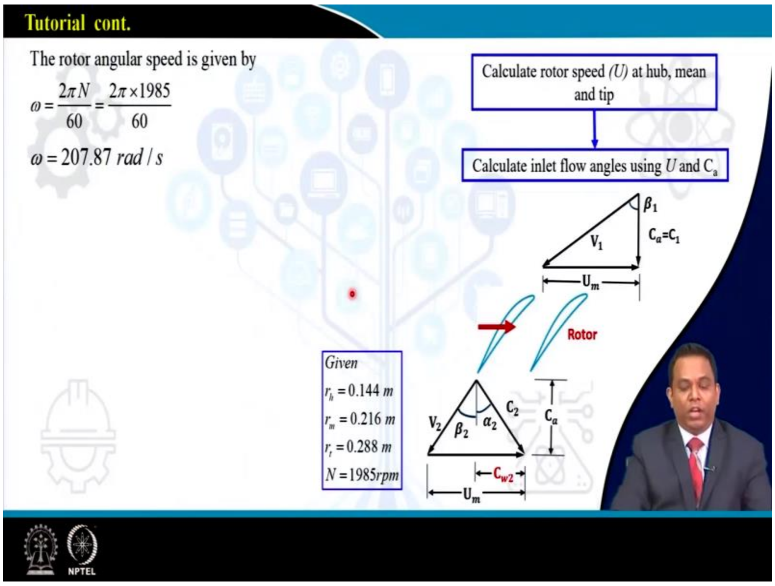
So, here if you look at, say what all data, that's what is given to us is say we know what is the rotational speed of our rotor, we have axial velocity as say 25 $m/s$, we have three radiuses at different stations, they are given, we have degree of reaction it is considered to be constant and that number is 0.55.

So, in order to solve this numerical, we need to go with the strategy, what all are the strategies? We know, in order to calculate the exit flow angle we will be using the equation for degree of reaction and that degree of reaction it say

$$R = \frac{C_a}{2U}(\tan\beta_2 + \tan\beta_1)$$

So, for this case at axial velocity, it is given that is constant, we are assuming. The peripheral speed we realize at different stations say hub, mid and tip section, that's what is depending on my radius. So, we need to calculate that parameter in sense of $\beta_1$ and $\beta_2$. So, we are given with say different values of say axial velocity and peripheral speed we can calculate what all are the angles $\beta_1$ and $\beta_2$ at different stations.

(Refer Slide Time: 12:09)




Now, let us move it. So, very first step for the calculation it is to calculate the peripheral speed at different stations and we will be calculating what all are the inlet angle, inlet blade angle or inlet air angle. So, what we know, the rotor angular speed, we can write down it is say

$$\omega = \frac{2\pi N}{60}$$

Since my rotational speed is given to me, say 1985 by putting that we are getting our angular speed as 207.87 $rad/s$.

$$\omega = \frac{2 \times \pi \times 1985}{60} = 207.87 \, rad/s$$

Now, this is what is known to us. Say, here if you look at, the peripheral speed that we can represent as say my angular speed into say radius. So, if you are calculating that. So, at hub, at mid-section and at the tip section, this radius are known to us, say they are 0.144, 0.216 and 0.288.

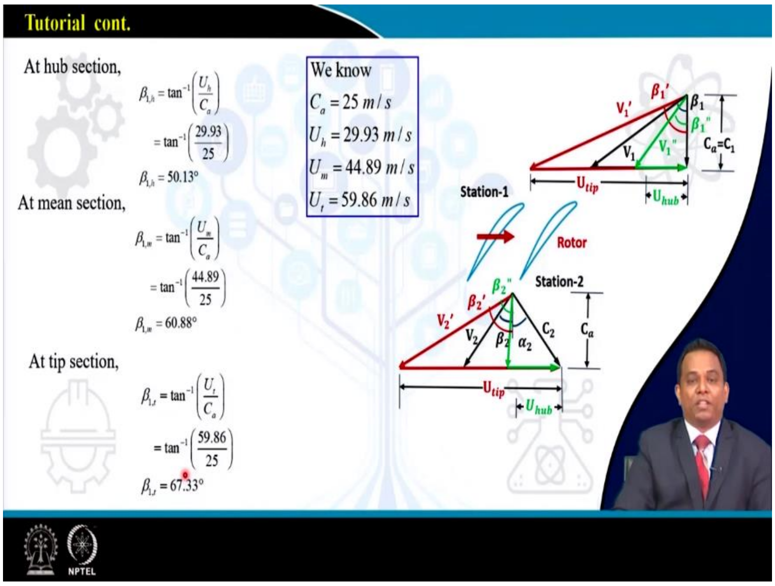
$$U_h = \omega \times r_h = 207.87 \times 0.144 = 29.93 \, m/s$$
$$U_m = \omega \times r_m = 207.87 \times 0.216 = 44.89 \, m/s$$
$$U_t = \omega \times r_t = 207.87 \times 0.288 = 59.86 \, m/s$$

So, if you are putting these numbers, that's what will be giving me my peripheral speed at different stations. Now, in order to calculate your angles at the entry, what we know? my tan beta 1 that's what is given by

$$\tan \beta_1 = \frac{U}{C_a}$$
$$\therefore \beta_1 = \tan^{-1}\left(\frac{U}{C_a}\right)$$

So, at different stations, we are aware of now our peripheral speed, we know what is our axial speed; so, based on that we can calculate what will be my blade angle at the entry or my air angle at the entry.

(Refer Slide Time: 13:52)




So, at the hub station, what we know? Say, this is what is representing how my peripheral speed that's what is changing at the tip. This is what is representing, what is happening at the hub station. So, in order to realize that part, what it say, at hub station I need to calculate what will be my peripheral speed, that's what we have calculated.

So, based on that, if we will be putting, it says my angle at the entry, that's what is,

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

this $U_h$ is known to me, Ca is given 25 $m/s$. So, my $\beta_1$ at the hub is coming 50.13°.

$$\beta_{1,h} = \tan^{-1}\left(\frac{29.93}{25}\right)$$
$$\therefore \beta_{1,h} = 50.13°$$

Same way at the mid-section, we can calculate my $\beta_1$ as say,

$$\beta_{1,m} = \tan^{-1}\left(\frac{U_m}{C_a}\right)$$
$$\beta_{1,m} = \tan^{-1}\left(\frac{44.89}{25}\right)$$
$$\therefore \beta_{1,m} = 60.88°$$

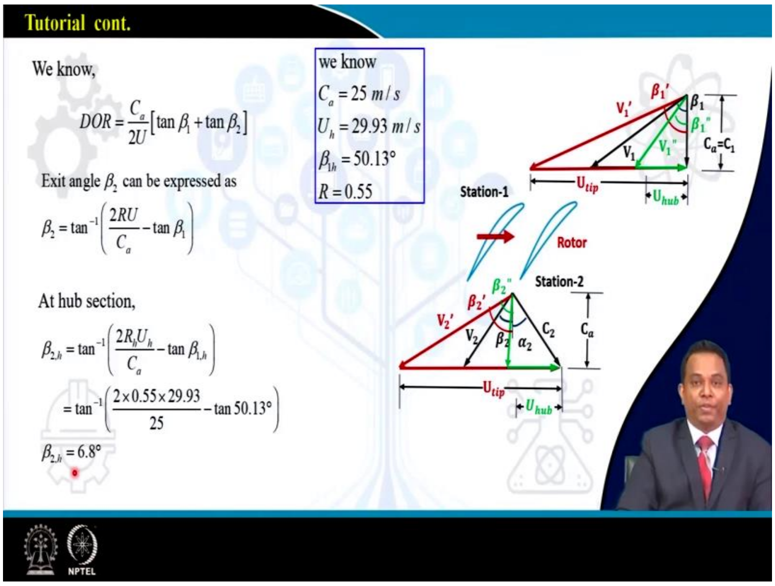
my peripheral speed at the midsection that's what is known to me it is 44.89 divided by 25 that's what is giving me my inlet angle that's what is 60.88°. In line to that we will be calculating our angle at the tip section. And that's what is coming 67.33°. So, these are the angles $\beta_1$ at different stations at the hub, at mid-section and at the tip section.

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

$$\beta_{1,t} = \tan^{-1}\left(\frac{59.86}{25}\right)$$

$$\therefore \beta_{1,t} = 67.33°$$

(Refer Slide Time: 15:25)




Now, what is our next step that's what is to calculate what will be my angles. Now, for calculation of our exit angle, what we know; we have our degree of reaction formula, that's what is

$$R = \frac{C_a}{2U}(\tan\beta_1 + \tan\beta_2)$$

In this case, if I will be writing, say my $\beta_2$, I can represent in the form of tan inverse equation.

$$\textit{Exit angle } \beta_2 \textit{ can be expressed as}$$

$$\beta_2 = \tan^{-1}\left(\frac{2RU}{C_a} - \tan\beta_1\right)$$

So, based on that, if we will be calculating at the hub station, we can calculate that by using the equation of degree of reaction. What is given to us, is say our degree of reaction is given 0.55, that is constant at hub, mid and tip section. So, by using this relation, we can calculate what will be my air angle at the exit at the hub station.

*At hub section,*

$$\beta_{2,h} = \tan^{-1}\left(\frac{2R_hU_h}{C_a} - \tan\beta_{1,h}\right)$$

$$\beta_{2,h} = \tan^{-1}\left(\frac{2\times 0.55\times 29.93}{25} - \tan 50.13°\right)$$

$$\beta_{2,h} = 6.8°$$

*At mean section,*

$$\beta_{2,m} = \tan^{-1}\left(\frac{2R_mU_m}{C_a} - \tan\beta_{1,m}\right)$$

$$\beta_{2,m} = \tan^{-1}\left(\frac{2\times 0.55\times 44.89}{25} - \tan 60.88°\right)$$

$$\beta_{2,m} = 10.2°$$

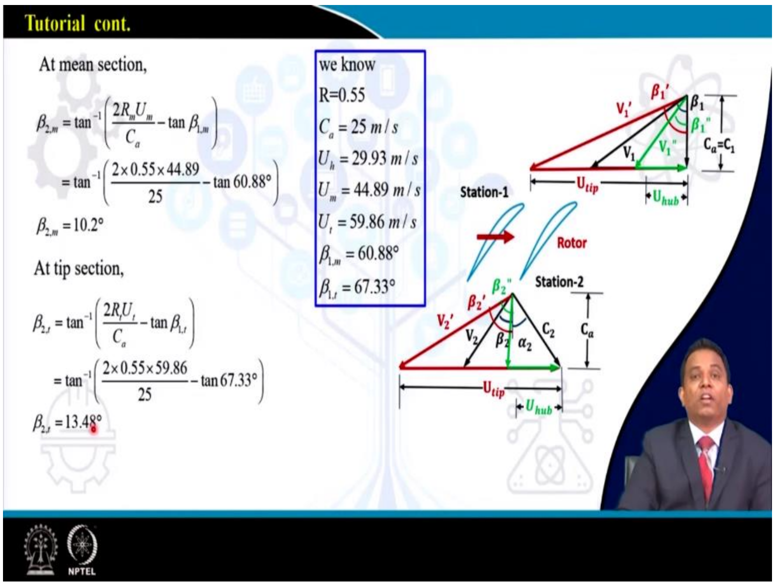
*At tip section,*

$$\beta_{2,t} = \tan^{-1}\left(\frac{2R_tU_t}{C_a} - \tan\beta_{1,t}\right)$$

$$\beta_{2,t} = \tan^{-1}\left(\frac{2\times 0.55\times 59.86}{25} - \tan 67.33°\right)$$

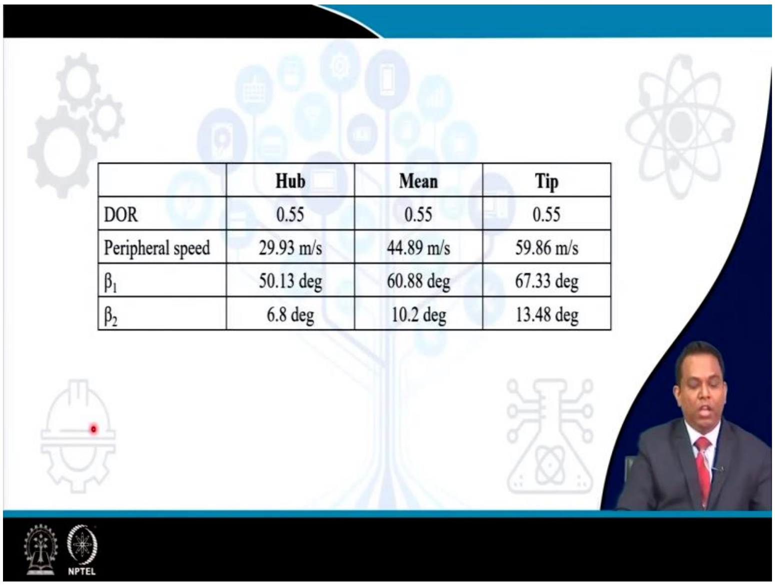
$$\beta_{2,t} = 13.48°$$

(Refer Slide Time: 16:30)



In line to that, we can calculate what is our angle at the midsection and that's what is coming 10.2°. Similarly, at the tip station also, we can calculate our angle and that angle is coming 13.48°.

(Refer Slide Time: 16:40)

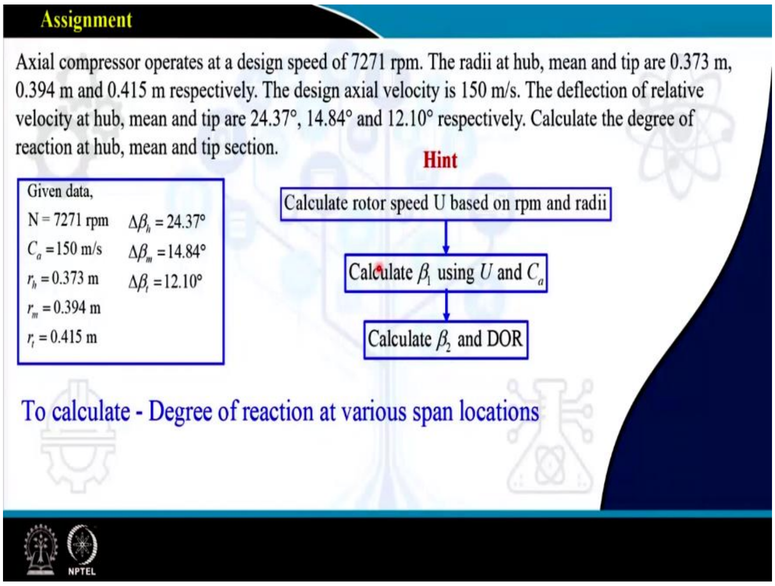


| | Hub | Mean | Tip |
|---|---|---|---|
| DOR | 0.55 | 0.55 | 0.55 |
| Peripheral speed | 29.93 m/s | 44.89 m/s | 59.86 m/s |
| $\beta_1$ | 50.13 deg | 60.88 deg | 67.33 deg |
| $\beta_2$ | 6.8 deg | 10.2 deg | 13.48 deg |

Now, in conclusion, if you look at, say what is given to us, say at three different station, we are given with our degree of reaction as 0.55. So, as I told, earlier people they used to do design based on the concept of constant reaction, okay and that constant reaction they are taking around 50%. So, early 60s and 70s what all engine you were looking at, those engines were designed with say degree of reaction to be constant and that was 0.5. So, this is what will be giving you some of the idea in sense of what all will be the change of my $\Delta\beta$ at different stations.

We will be discussing in next session for week 3, what all are the concepts for designing and there we will be discussing in detail, what is the meaning of degree of reaction to be constant at particular station. So, for this instance, this is what will be giving you idea how you will be using your concept of velocity triangle and how you will be calculating or your degree of reaction. If it is known to you how you will be doing your reverse calculation for the calculation of your blade angles. So, after doing this, I am sure you may be able to do the numericals based on this kind of concept.

(Refer Slide Time: 18:09)




So, for assignment take one example. Let me discuss about that, say axial flow compressor that operates at design speed of 7271 rpm. The radius at hub, mean and tip section are 0.373-m, 0.394 m and 0.415 m, respectively. The design axial velocity is 150 $m/s$. The deflection of relative velocity at hub, mid and tip section are 24.37°, 14.84° and 12.1° respectively. So, you need to calculate what will be the degree of reaction at hub, mean and tip station. So, let us see what all data that's what is given to you.

The data given is your rotational speed is known to us, our axial speed is known to us, we are given with different stations say hub radius, mean radius and tip radius. You are given with $\Delta\beta$ that is nothing but the deflection angle, at the hub it is given 24.37°, at midsection it is 14.84° and at the tip section that's what is say 12.1°. And what you need to calculate it is you need to calculate your degree of reaction at different stations.

Now, in order to solve this numerical, let me give you a hint. Say, you are given with, say your rotational speed, that's what will be helping you in order to calculate your peripheral speed. Your axial velocity is known to you. Based on that, you can calculate your inlet angle. You can calculate your, say exit angle. And based on that you can calculate what will be your degree of reaction. So, see you in the next class. Thank you! Thank you very much for your attention!