Aircraft Propulsion

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Lecture-39
Cascade variables and turbine cascade

Welcome to the class, we were discussing about the blade design and cascade theory. In the last class, we had seen that how a blade of cascade can be mounted in a tunnel which is a blower type tunnel what are the different parts of a blower type tunnel are other cascade tunnel where it is mounted and then what are the different properties we measure how do we measure direction of velocity, these are the things which we had seen.

Now, these are the parts or this is the process in which blades are designed. We are going to see the further things which are involved in the cascade theory and blade design process.

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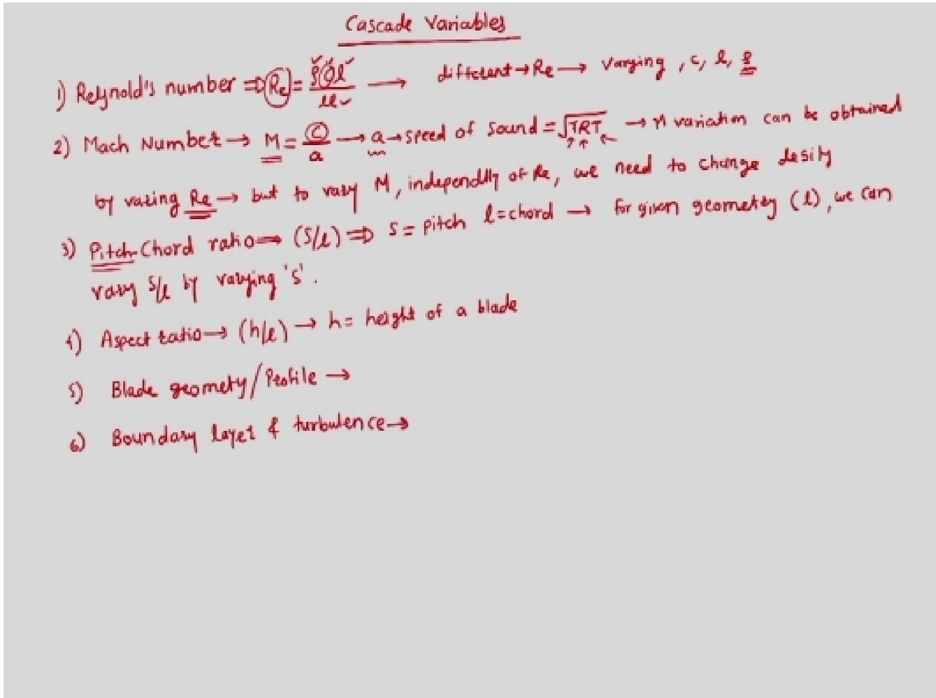
Here we have to do experiment while designing a cascade or blade with different Reynolds number different Re and these experiments with different Re can be done by varying c, which is velocity or we can vary l or we can vary the density if we are working with compressible flow, but if we are working with incompressible flow, we cannot vary the rho which is required or we need to go with high pressure gases for the expansion.

Not just, the atmospheric gas so, second variable which is there which is Mach number. Mach number by definition $M = \frac{c}{a}$, where we know a is speed of sound and it is equal to $\sqrt{\gamma RT}$, γ is specific heat ratio R is particular gas constant, T is the temperature at which we are finding out the a. Now, as we see Mach number involves c. Reynolds number also involved c so, prominently Mach number variation can be obtained by varying Reynolds number but to vary Mach number independently of R_e.



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We need to change density and this is a tough task. Third variable which is there for in the cascade variables is pitch to chord ratio we know chord called is the distance between leading in trailing edge of the Aerofoil we are going to see these terminologies further pitch is the spacing between two blades in the rectilinear cascade. So, this pitch to chord ratio can is one more parameter in the cascade variables and this is $\frac{S}{l}$ where S is equal to pitch and l is equal to chord.

And then, this to vary we need to vary basically the spacing for given geometry that is l we can vary $\frac{S}{l}$ by varying s here, we will hear, we can dismantle the cascade where we would have put multiple number of blades and now after dismantling. We will reassemble the cascade by alteration by altering the spacing between the two blades. So, this is how we can vary the pitch to card ratio fourth is aspect ratio.

Aspect ratio is for a particular blade which is defined as $\frac{h}{l}$ where h, is height of a blade and l is chord. So h by l is the aspect ratio, we can vary aspect ratio by varying h or by varying l for a given geometry again we cannot vary l so, we have to vary h. h is the height of the blade, which we can vary, but we know that this cascade would be mounted at the end of the tunnel and then we have to vary the test section and the contraction for that all sake where we are interested to vary the aspect ratio through variation of the blade height, this is a tough task then fifth variable is blade geometry or profile in the process of blade design we should test different blades for their performance for a given turbo machinery application. So, the profiles on geometries of the blades which we would have decided which we would have defined.

And those geometries are those blades should be tested in case of the their testing in the cascade tunnel so, we should vary the geometry or what we say it as the profile of the blade to assess its performance. So, next variable is boundary layer and turbulence we have seen here that the cascade receives the boundary layer from the contraction and test section it is invariant how would be the perfect contraction we implement.

We still would have certain thickness of the boundary layer which is received by the cascade, we have also seen that we put porous walls so, as remove the decelerated flow. So, to see the effect of boundary layer, which is received by the cascade, we can change the porosity of the material which would be actually absorbing decelerated flow by that, we can vary the thickness of the boundary layer received by the cascade further.

We can vary turbulence or intensity of turbulence, which is present at the entry to the cascade. For that variation of turbulence, we can do few things where we can put different kind of turbulent generators, and those turbulent generators can be for variation of turbulence, we can put different turbulent generators such as the turbulent grids upstream of the cascade and those turbulent grids can generate different amount of turbulence received by the cascade.

Further, the type of the boundary layer is also governing parameter, which can again be laminar or turbulent and that depends upon the Reynolds number. So, Reynolds number is the first parameter, at the cascade variable here, if we vary the Reynolds number that itself would vary the amount of turbulence or maybe the nature of the flow which is received by the cascade.

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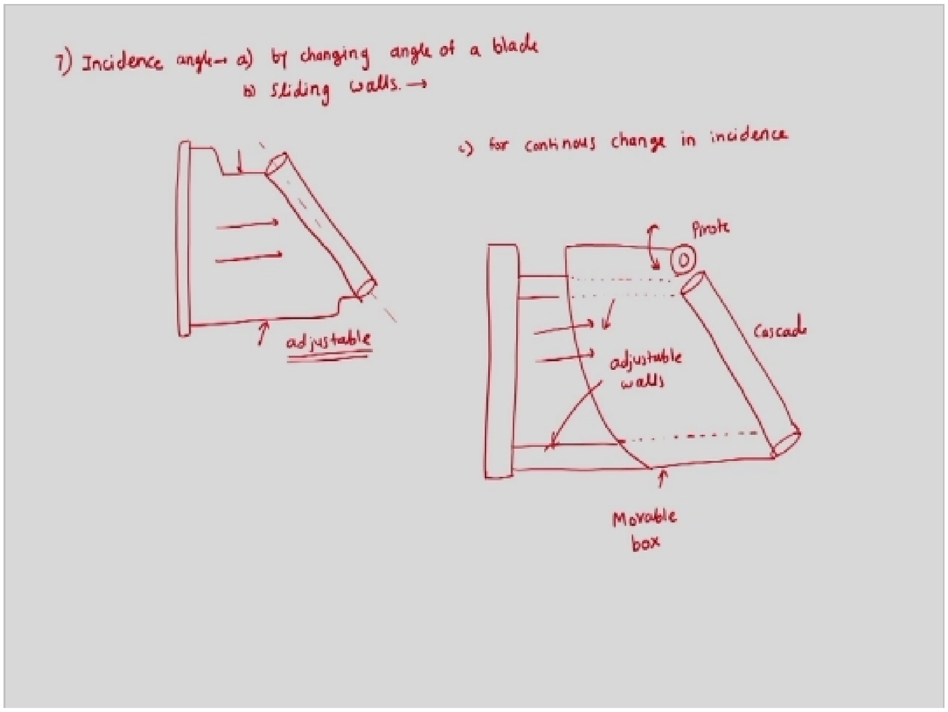
Set it to the desired angle and then this would be continued for all the blades and then all the blades would be set for the desired incidence angle and then we can test it for the different incidences so, first a is by changing angle of a blade and second option over here is having sliding walls so, second option is sliding walls. In case of sliding walls, we can do different arrangement that we knew that this is the test section of the cascade tunnel.

And then in this test section we can keep the sliding walls and then this cascade will be mounted at the end of the sliding walls. So, this is the conventional way by which we would be mounting the cascade, this is velocity vector and then this is the direction in which cascade is at this moment mounted but this wall and this wall if we can keep adjustable then we can change the orientation of the cascade and hence the inclination.



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Then there is one more option which is for continuous change in inclination or incidence continuous changing incidence here cascade is mounted on a pivot and which is operated continuously such that the orientation of the cascade would change with respect to the flow. So, this is cascade. Now, this cascade will be put on a pivot and this pivot is rotating the cascade. So, this is adjustable wall this is also adjustable wall.

These two are adjustable walls and then this is a movable box and then this is pivot on which the cascade is connected with so, this pivot would rotate the cascade in different angles and then it will change the orientation of the cascade with respect to the velocity vector and hence, it can alter the incidence angle of the flow. Now, this all was related to the testing of a cascading a tunnel and then that tunnel we have talked with about is the cascade tunnel.

So, now we have understood what is a cascade tunnel what are the different ways by which we can major different things in a cascade tunnel and also how to alter different variables or performance parameters for a cascade in a cascade tunnel. Now, we will see few things related to blade and then then we will see how the turbine cascade will be there and how the compressor cascade will be there and what are their basic parameters for the derivation.

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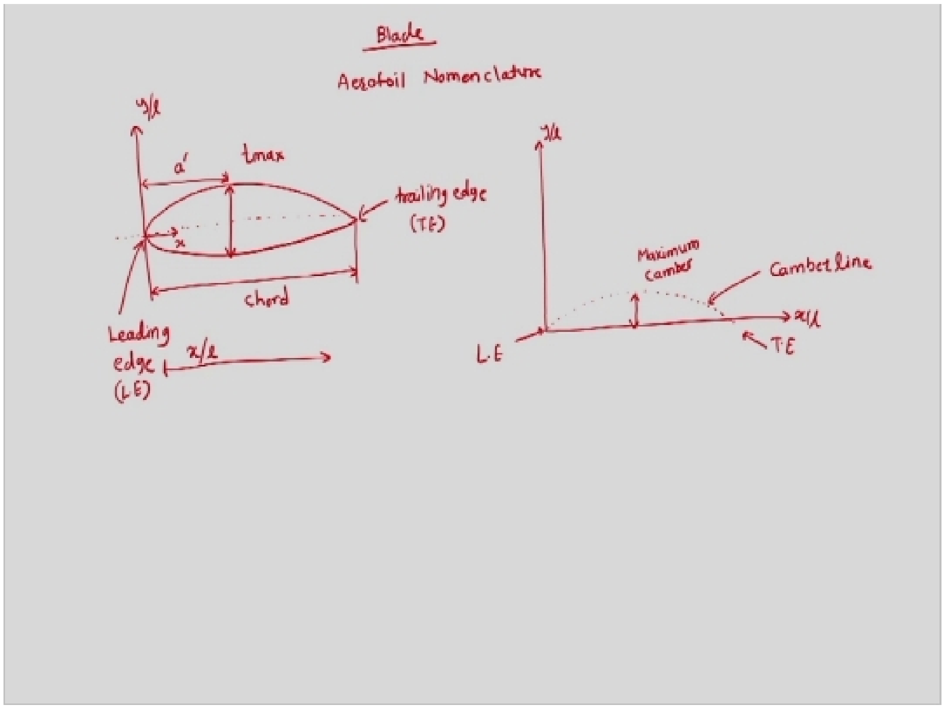

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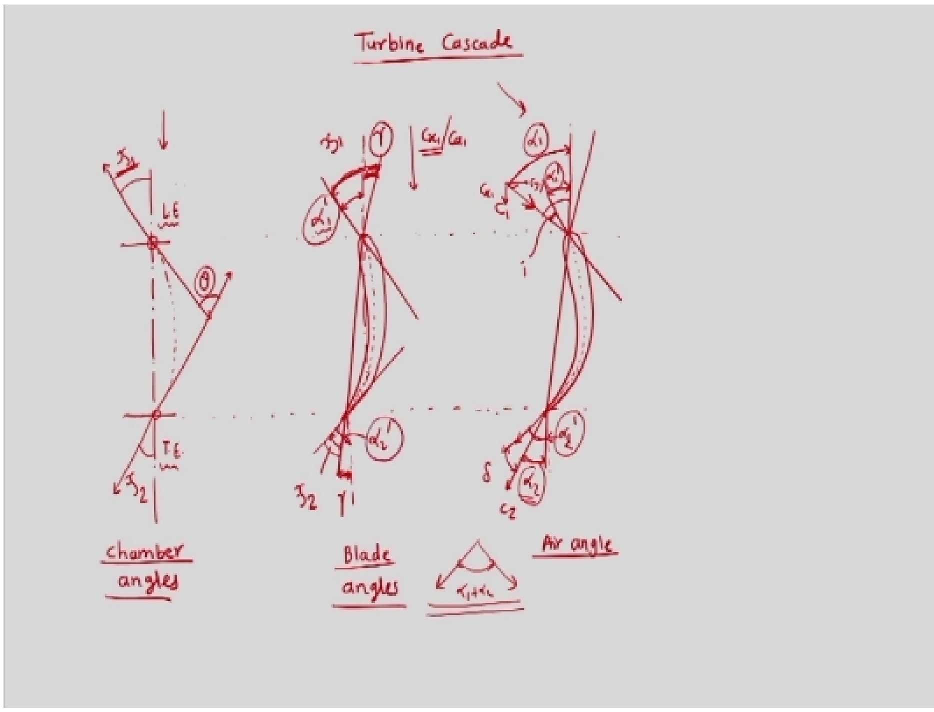
as this as the axis which is also called as the chord if we measure the distance between the leading edge and trailing edge so, this if we take it as y axis and this if we see it as x axis, this is the location of maximum thickness and then this maximum thickness is going to appear at a particular distance see a dash and then this is chord.

So, this x axis is basically defined as the x location divided by maximum x location which is chord. So, this axis is $\frac{x}{l}$. So, parallelly y axis would also be normalized with and as $\frac{y}{l}$ having said this, there is no curvature in the Aerofoil. So, if we have curvature in the Aerofoil then same $\frac{y}{l}$ and $\frac{x}{l}$ axis so, this Aerofoil with curvature is this so, this time this is curved center line is called as camber line and then this is leading edge, this is trailing edge.

So, we will say it as LE and TE and this is the maximum curvature this is called as maximum camber location of the Aerofoil. So, these are the nomenclatures of Aerofoil cross section. Basically, the turbine blades or the compressor blades will have a particular specific cross section and those cross sections are generally Aerofoil kind of cross sections since, Aerofoil is a shape, which is preferred.

Since, it gives least drag and it gives us desirable lift it can give for a particular shape it can give lift and with lesser drag it is a streamlined object and then different labs are old all over the globe have defined different Aerofoils, such as there are European Aerofoils, NACA Aerofoils and then those Aerofoils would have different shapes and those shapes would have different performances, since they are defined for their own applications.

So, we can use either such Aerofoils or design new Aerofoils for the applications of ours for the turbo machine.



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(refer time: 20:02). Now, we will see turbine cascade by saying turbine cascade, we are saying that the turbine blades are put in the tunnel in a specific order which is called as in the rectilinear tunnel a rectilinear cascade in a specific order of spacing which we have specific geometry chord length and then specific camber. So, that blade is kept in a tunnel and then how that cascade will look like that is what we are seeing over here.

So, this is having certain nomenclature again so, let us first plot the cascade so, we know we have to put multiple number of blades while thinking of a cascade in the tunnel so, here first let us say that this is the chord line and so that this is leading edge and this is trailing edge of the Aerofoil and then this is the chamber line of the Aerofoil and since this is chamber line of the Aerofoil we should know what are the different angles.

So, this camber line we can draw a tangent at the leading edge. So, this is tangent at the leading edge, then we can draw a tangent at the trailing edge. So, if we draw a tangent at the trailing edge both the s will meet at a point and then they make an angle θ, which is called as a chamber angle, but this tangent at leading edge. So, this is the direction of flow for us so, flow is coming from this is that is why this is a leading edge, this is a trailing edge.

So, at the leading edge, the tangent makes an angle so, this is χ_1 and then at the outlet it is making an angle this is χ_2. So, this diagram is called as a diagram for chamber angles. Now, we will draw a diagram for blade angles we have seen in case of cascade or in case of turbines or in case of compressors while drawing the velocity triangle there are certain blade angle there are certain nozzle angles.

So, among in those terminologies equally we are making the blade angles and chamber angles. So, blade angles over there was the angle for the relative velocity in the cascade tunnel, the blades are stationary. So, the velocity absolute velocity is going to make certain angle. But these blade angles over here are defined in a different way we are just going to draw that so, this is suppose again the axis this is our Aerofoil.

Now, this is the camber line. So, for the camber line again we can make one tangent at the inlet and we can make one tangent at the outlet. So, having said this, so, this is the line which is joining the leading edge and the trailing edge this is the chord line. So, this joint line joining leading edge and trailing edge will be making certain angle with the vertical axis and then that angle is called as stagger angle γ and we have seen that the tangent making an angle with the chord line we are already calling it as χ_1.

So, this angle, which is now χ_1 - γ it is called as $\alpha_1^{'}$ which is a blade angle at the inlet. So, similarly, we can make this tangent with vertical axis as this tangent with the chord line as χ_2 then this vertical line which the tangent as what we made over here as $\alpha_2^{'}$ and then we have this small angle as the stagger angle these are the blade angles α_1 and α_2. Now, we will show the same blade where we will add the velocity vector.

So, this is our Aerofoil and this is the camber line of the Aerofoil. So, this is the vertical line here, this is the vertical line here now, this is the direction of tangent and then let us feel that this is the way by which flow is approaching and this is the C_1 absolute velocity vector. So, and then we have the chord line as this so, velocity vector making an angle with chord line is α_1, which is called as air angle similarly let us feel that the velocity vector is going here as C_2 this is making an angle with the vertical line is α_2.

We know what is α_1? α_1 is the angle made by the tangent with the vertical line, this is α_1 rather $\alpha_1^{'}$. Similarly, we can show here and that this is the tangent, which is making an angle which is $\alpha_2^{'}$ so, in this fashion, we would have different angles defined, we will revisit these angles again.

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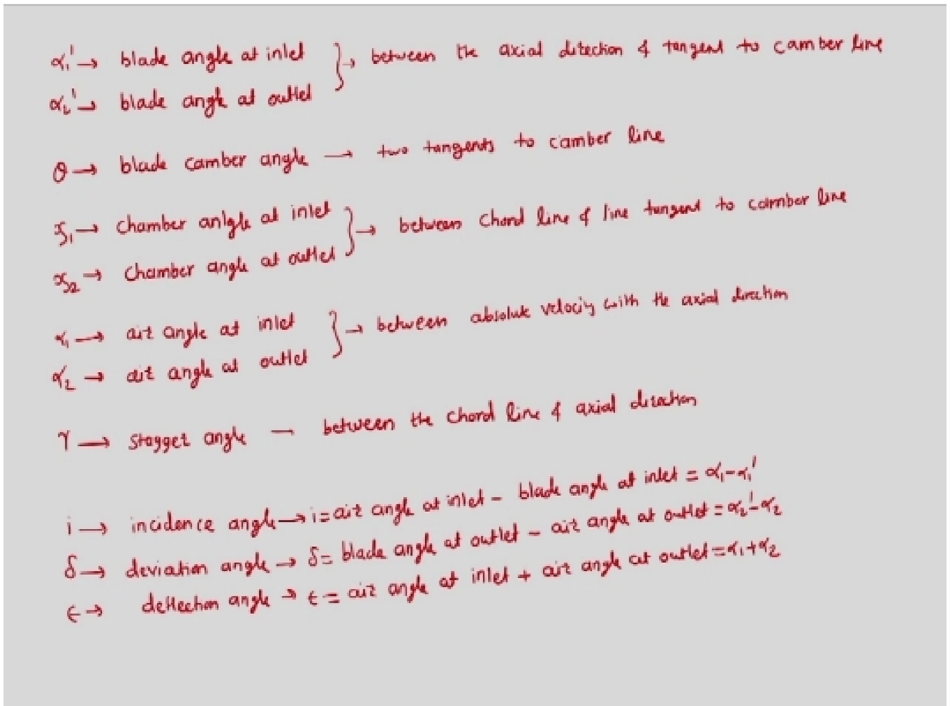

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at inlet then χ_2 chamber angle at outlet. Then we have α_1 and α_2 which are air angles, so α_1 is air angle at inlet α_2 is air angle at outlet.

Then we have gamma, which is stagger angle then we have new angles which are defined one is i. i is called as incidence angle, we will define it then we have delta, it is called as deviation angle and then we have the epsilon, which is deflection angle and we will see these 3 angles before that we will revisit how we have got these angles we got α_1' and α_2' has 2 angles which are between the axial direction and tangent to camber line.

So, if we go back we see that α_1' and α_2' these 2 are the angles between the axial direction so, this is the velocity vector, this velocity vector has 2 components, 1 is C_{x1} and other is C_{y1}. So, this is the direction which is of C_{x1} so axial velocity or in our language this is C_{a1} which is the axial direction of velocity so, the angle, are made by the tangents with axial direction is what α_1' and α_2' at the inlet.

Theta is the angle between two tangents to camber line. Then χ_1 and χ_2 are the angles between the chord line and line tangent to camber line we can see this so, this is a tangent at the leading edge this is the tangent at the trailing edge, both the tangents meet at θ which is tangent angle so, χ_1 is the angle between chord line. Chord line is a straight line which is joining leading edge and trailing edge.

So, this straight line makes an angle χ_1 with the tangent, the camber line at the inlet and χ_2 to the tangent at the outlet. Same way here thus the chord line is inclined so this chord line or here is perfectly aligned with the axial direction here chord line is not perfectly aligned with the axial direction. So, we have χ_1 made with the straight line joining leading edge and trailing edge and the tangent.

So, this α_1 and α_2 are the angles between velocity vector absolute velocity and axial direction. We have seen this absolute velocity C_1 makes an angle this with the absolute velocity with the chord line. So, we have seen this, that the absolute velocity, C_1 is making an angle α_1 with the chord line which is called as air angles similarly, this is with the same at the outlet α_1 is the angle made by the velocity vector with the vertical line or the axial direction. So, this is α_1.

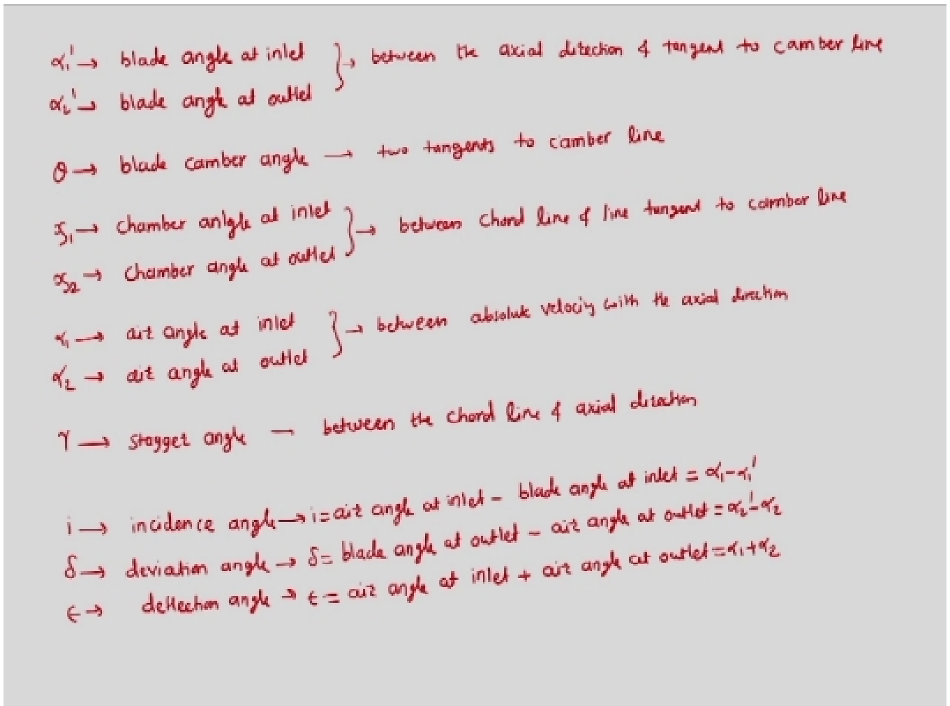
Similarly, α_2 was the angle made by the velocity vector with the vertical line. So, these are the angles having said this, so, it is with the axial direction now, γ is the stagger angle. Now this stagger angle is between the chord line and axial direction if we see it is the chord line, line straight line joining leading edge and trailing edge and the axial directions this is the γ, which is stagger angle and this stagger angle is used for the setting of the cascade into the tunnel.

So, it is mostly experimental number which is used for the convey so, then we have new angles which are defined and then incidence angle i is basically defined as air angle at inlet - blade angle at inlet, so, it is α_1 - $\alpha_1^{'}$. So α_1 if we see then it is the angle between the axial direction and absolute velocity and then $\alpha_1^{'}$, which is the α_1 is the air angle $\alpha_1^{'}$ is the blade angle between the tangent at the inlet to the camber line and axial direction.

So, this α_1- $\alpha_1^{'}$ is this small angle, and the small angle is incidence angle, then we have δ and this δ is called as deviation angle and then this is δ is equal to blade angle at outlet - air angle at outlet hence it is $\alpha_2^{'}$ - α_2 same way over here we can see $\alpha_2^{'}$ - α_2. So, this is $\alpha_2^{'}$ which is angle between the tangent to the camber line and the axial direction and then C_2 is the velocity vector.

So velocity vector and axial direction, this is α_2. So, having these 2 difference here as delta, which is the deviation angle and deflection angle which is ε = air angle at inlet + air angle at outlet. So, this is $\alpha_1 + \alpha_2$. So, if we see that air is coming in this direction at the inlet and going in this direction at the outlet so, air is getting deviated or rather deflected by a complete angle, which is $\alpha_1 + \alpha_2$ between the inlet and outlet.

(refer time: 38:38). So, this is deflection angle now, we have one more thing to remember over here that we define θ, which is chamber angle, it is $\chi_1 + \chi_2$ similarly $\alpha_1^{'}$ is χ_1 - γ we can see so, χ_1 is the angle which is here and then this is gamma. So, χ_1 - γ is $\alpha_1^{'}$. So, we are writing $\alpha_1^{'} = \chi_1 - \gamma$. Similarly, $\alpha_2^{'} = \chi_2 + \gamma$ can we can go at the outlet and see. So, this is χ_2



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this small angle, this is γ and this is α_2'.

So, α_2' is summation of 2 angles. So, now, if we make $\alpha_1' + \alpha_2'$, then we get $\chi_1 + \chi_2$ so chamber angle is $\alpha_1' + \alpha_2'$ which are blade angles and then which are equal to $\chi_1 + \chi_2$ which are chamber angles. Now, we can write one more thing for deflection angle which is $\alpha_1 + \alpha_2$. So, α_1 is α_1' + i and α_2 is α_2' - δ.

So, $\varepsilon = \alpha_1' + \alpha_2'$ + i - δ. So, from here we can write it is equal to θ + i - δ. So, this is the definition of deflection angle or other derivation of deflection angle having said this, now, we need to find out what is the basically way by which the direction of forces are defined which are getting applied on a cascade and then how to find out using the derivations which involve set mathematical relations. We will see this in the next class. Thank you.