Introduction To Flight
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Lecture 05.6
Lift Generation by Wings: Part I

So now next theory, the skipping stone theory or the theory in which momentum is transferred, I also call it as a bullet theory, so you fire a bullet there is a reaction so let us see.

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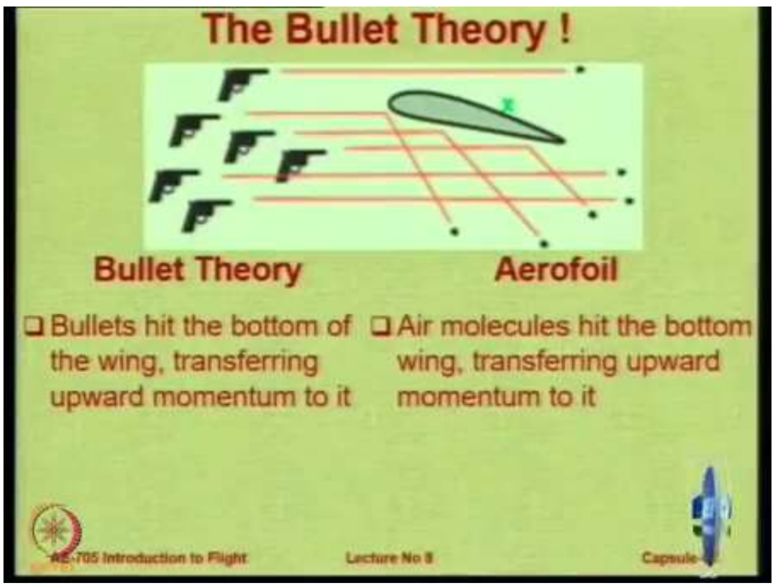

So, what is this bullet theory? The bullet theory says that you have an aerofoil type body at a particular angle, ok, or no angle but you have curvature, in this case the bottom surface is almost flat, the top one is curved and we have also put it at some angle. Now we are firing these bullets, what are the bullets? The bullets are the flow particles, the fluid particles.

So the particles above or little bit away from the aerofoil are going straight; undisturbed because they do not hit the body. The particle which is hitting the body is being deflected downwards and the deflection depends upon the curvature of the local part. So, in the bullet theory we have bullets hitting the bottom of the wing transferring momentum to it which is offered and in aerofoil it is true that the air molecules that hit the bottom wing, they transfer the upper momentum to it. Nothing wrong in these two, these two analogies are correct, ok. And a large part of lift a non-trivial part of lift is generated by this principle also. So, we are not saying it is wrong but we are saying that this is not the only way of doing it. And now let us see how we can debug this theory for many-many scenarios.

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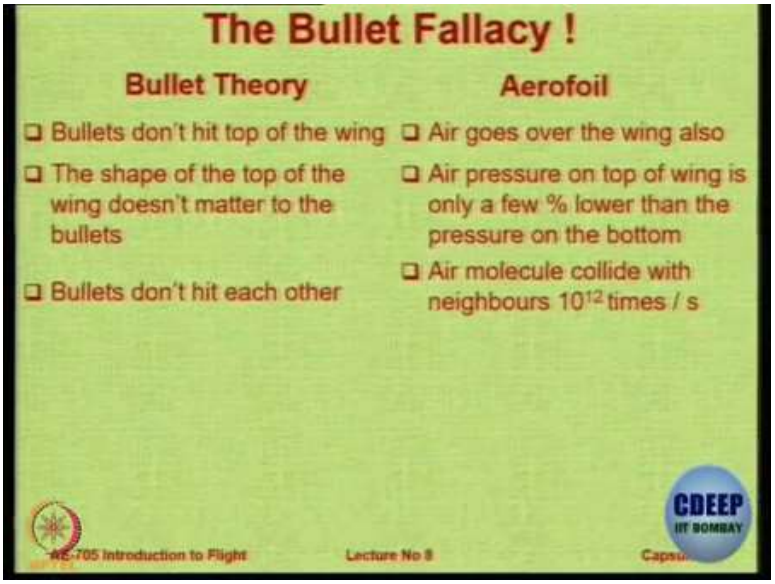

The first scenario is that in this particular example the bullet does not hit top of the wing, they go above the wing therefore, according through this theory, the particle which flow just above the aerofoil should not be disturbed, they should go straight. But we have seen that the particles that are flowing above the wings do not go straight they also bend down. The particle that go below the wing also bend down, the particle which go above the wing also bend down, the particles which are very far away from wing they do not bend down. But a particle which is just above the wing also bends down. So, this is one place where the bullet theory fails.

Secondly, the shape of the wing does not matter to the bullets, except for the angle of reflection. Whereas, the air pressure on the top of the wings is only a small percentage lower than the pressure on the bottom, ok so, there will be a difference, but it does not matter as far as the bullet is concern. The bullets are all going parallel, they do not hit each other but air particles are not always flying parallel, air particles are actually colliding with each other and you know there is something called as kinetic theory of gases which tells you about the general phenomena of Brownian or normal motion. In the Brownian motion the air molecules are colliding themselves huge number of times so they are not a bunch of bullets moving independently, they are actually a huge number of bullets which are colliding with each other and also moving around so, this is something that is not taken care.

Now, bullets are going to weigh reasonably large some grams, 5 grams, 10 grams, etc, so they have a huge momentum because of mass, ok. Air molecules are very very light, ok. They may be large in number but they are very light. So, if momentum is the only way, the momentum of the air transferred to the wing is actually quite small so just by momentum you cannot get a lift. So, you cannot fly an airbus A380 with thousand passengers just by the momentum transfer of some air particles simply below the wing too much to expect that just by momentum of air you will get such a large amount of lift, ok. So, the bullets that miss the wing above, below they are undeflected, but you know that far below and far above the wing ok, in fact it is generally said that if the wings span is 10 meters then roughly 10 meters above and 10 meters below the aircraft the fluid is disturbed. The level of disturbance is highest near the surface and as you go up the level of disturbance reduces but as per the bullet theory if you miss the wing you are unaffected, ok.

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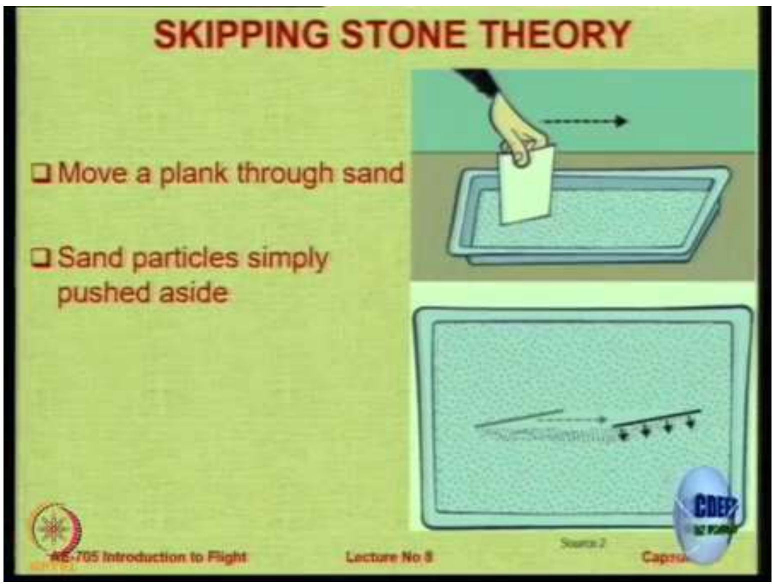

So, what does skip skipping stone theory say? The skipping stone theory says that take sand, take a plank or take kind of a dish put sand on it, represent sand as molecules of air and you take this plank ok, this is a plank you have sand here and you just move it like this. So as you move it like this and if you give a small angle so you give a small angle and move it like this. So the particles here will be moved aside, the particles below will be moved down and the plank will move forward, this is called as a skipping stone theory or the theory so in this particular case the sand particles are simply pushed aside, ok. So, here also the same argument is given that as you move these particular planks the momentum moves the reaction of the motion of these planks into these beds of sand actually deflects the sand downwards ok.

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But the same does not happen when you move a plank through fluid ok, because air and water ok, they are not sand, air and water are not sand, they are different. Sand is not fluid, sand consists of distinct particles. ok, fluid consists of much more than just sand. So, the behaviour now in certain situations flow of sand can also be similar to the flow of a fluid I am not denying that but I am just saying in general you cannot equate water and air or fluids with sand. So, in fact when we move a plate through water or wing through the air what happens is not, what we saw for the motion of sand in a plank. So, can you tell me what is the difference? If you move a plank a plank into sand and if you move it through water, is there any difference in the flow?

In case of sand, the sand is simply pushed aside. In case of water or air something more happens, let us see what happens. So, when you swirl when you move a plank through water you can try it out you can try it in bathtub or any experiment you will see that there is some swirling which takes place especially in the front portion. The water will actually move from below the plank to above the plank in the front ok, as you move it and this is because there is a diffusion, fluid undergo diffusion and some kind of a circulation rounded flow gets created. You can try the experiment next time; you just move your hand in water you will not see that the water gets directly pushed behind I had its starts curling.

So, there is something different the phenomenon is a bit different when you move it through sand or when you move it through fluid like water. So, let us see what this particular thing is? This particular behaviour or this particular phenomenon is called as circulation.

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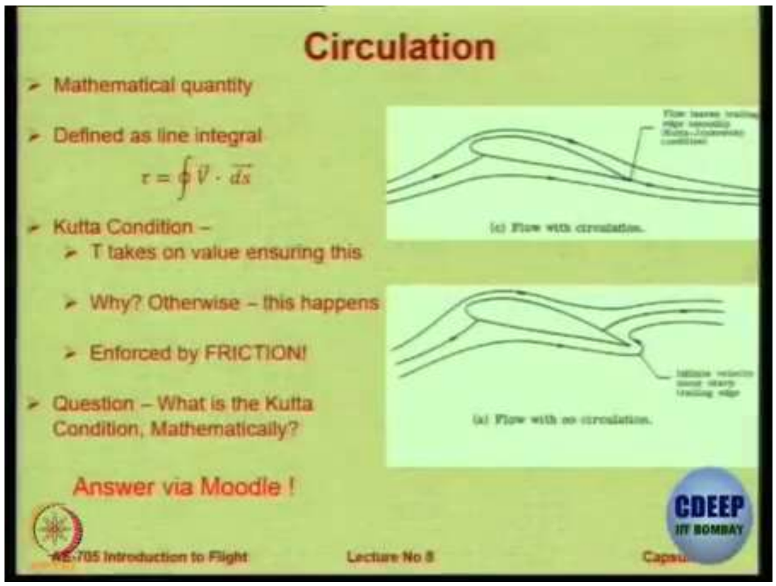

And circulation is basically mathematical quantity. Circulation is used by the aerodynamicist to try and describe the amount of rotatory motion created in a fluid when you move a body or presence of body in a fluid stream or motion of a body in a stationary fluid or whenever there is a relative velocity the phenomenon that causes curling of fluid is called as circulation and mathematically it is defined as a line integral.

So what you do is, around the body you just take the integral of the local flow velocity into ds which is a directional vector. So you go around the body so, basically you put a string around the body and now you traverse on that string and just do the line integral ok, you do this so not a line integral contour integral of the velocity and ds value and if you find that the net value of the integral is 0 that means the amount of water that curls this way is same as the one curl this way exactly the same. When I say amount, I do not mean the numerical value I mean the integral V dot ds then you can say the circulation is 0 because whatever rotational circulation has been imparted same has been cancelled by the other direction ok, but when you actually do the integral you find the value is non zero there is a net circulation still remaining ok. And therefore we come up with the definition of a condition called as a Kutta condition.

And this Kutta condition is basically a condition that, when you actually put a body in flow in a fluid flow, and you have this particular flow we observe that the flow leaves trailing edge smoothly. Now this is something that is experimentally verified, it leaves the trailing edge smoothly. Now it cannot actually unless there is some value of circulation, because if you do not define some circulation then this is what will happen and that means the flow is going to have some infinite velocity at the trailing edge. So at the sharp trailing edge, the flow will undergo infinite velocity because from a direction this way it has to now flow that way so this cannot happen.

And for this not to happen or for the flow to leave trailing edge smoothly, there is a necessity that there is some physical quantity called circulation, which acts in such a way that it actually pushes the point of flow reversal up to the trailing edge so that the flow leaves trailing edge smoothly. So this is basically and this is enforced by friction, this condition is imposed by friction ok, if you have frictionless flow which is theoretical or if you have on paper some kind of a theoretical flow where you can assume friction to be 0 then you may encounter such flow patterns. But in reality, there is friction present, there is viscosity present and therefore you will see that it leaves smoothly.

So, one way of encountering this or one way of imposing this condition is that the velocity just above and just below the trailing edge V1 up and or V tip up and V tip low is exactly the same, this is one way in which we can numerically impose and there are other ways also in which we have to impose. So the question for you is, what is the kutta condition imposed mathematically? ok, and this question I want you to answer via Moodle because I want you to read up about kutta condition, I want you to understand why this condition has come about, who is kutta? Who is the person who gave this condition? How did he do it? How are we going to apply it and what happens if we try to investigate a flow without putting this condition what happens? Do you get no lift, do you get less lift. So do some research on this condition, look at the historical development and educate us using the Moodle ok, let us proceed further now.

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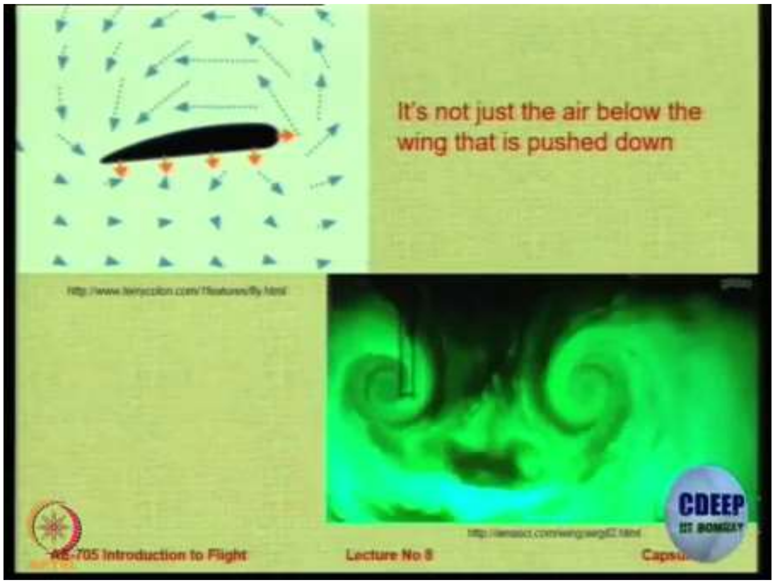

Another important observation which I would like you to make is that it is not just the air below the wings that is pushed down. In the skipping stone theory what you expect is that air above is not going to be disturbed too much but the air below is going to be pushed down. Actually, you can see that there is circulation because of which all across the flow field there is some kind of a circulation setup, ok. The other thing which is very important is that this particular video.

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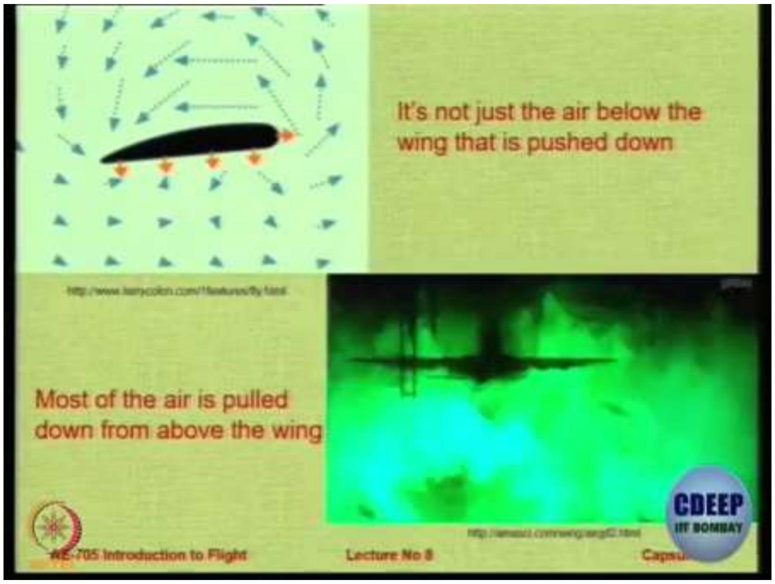

So, you see this particular plane is made to fly through a stationary almost stationary stream and what you observe is as the plane goes ahead, the air above the wing quite from quite far away is also being pushed down. So, most of the air is pulled down from above the wing. So, there is some kind of a suction created above the wing also, the air below the wing anyways being pushed down, but the air above the wing is also being pushed down and we observe another interesting thing in this small GIF file is that at the tips something interesting is happening.

At the tips the air is being pulled down but, it also goes into some kind of a vortex, ok. So it is not that just the air is being pushed down, the air is pushed down above the wing, the air is pushed down below the wing. At the tips the air is curled and it goes down and this curls actually moves down, this particular phenomenon that you are seeing at the tips is called as the wing tip vortex and this wing tip vortex is responsible for one kind of drag called as the induced drag, we will read about it.

I think the next lecture is going to be on drag and various components of drag. So for any lifting vehicle or any lifting aircraft, induced drag is very large component and the numerical value of induced drag will depend upon the strength of this vortex. So, if you want to reduce the induced drag you must do something so that strength of this vortex or the speed at which the air is curling and the size of this particular vortex it has to be curtailed, both the speed and the dimensions of this vortex. And to do that we use some devices at the wings called as wing tip devices. There are various types of wing tip devices, many of them are called as winglets. Even in winglets there are many types, there is just a simple winglet, there is a H-shape winglet, there is a L- shape winglet, all kinds of winglets are available. Whatever they may be, the main purpose of winglets is to somehow reduce the strength of these vortexes.

And some smart people have also suggested that this curling motion of air at the wing tip, why cannot we use it to generate power? By putting some small turbine type of devices there and you are getting this circulatory wind at very high speed so, use it to generate some powers, use it to drive a small fan.

So people have proposed many things they are possible but then one should look at the cost, complexity and weight because of providing such devices, so most people have decided to use passive devices like winglets to minimise the tip vortex strength ok. So, skipping stone theory would not be able to explain this particular phenomenon. Similarly there is venturi theory, venturi theory also as I mentioned to you says that because of the top curvature there is a nozzle type effect, that is not true because actually there is no nozzle compared to the free stream up and free stream below the thickness of the wing is very small and if that is the only reason then the effect should be very-very small.

So kilometres above the wing and kilometres below the wing there is free stream and just by that if you say nozzle effect. So, lets us look at actually what is happening and now we try to answer the question of how lift is really generated? Ok so we will look at the new idea called as a stream line curvature ok, and that particular idea should explain what we are trying to understand.

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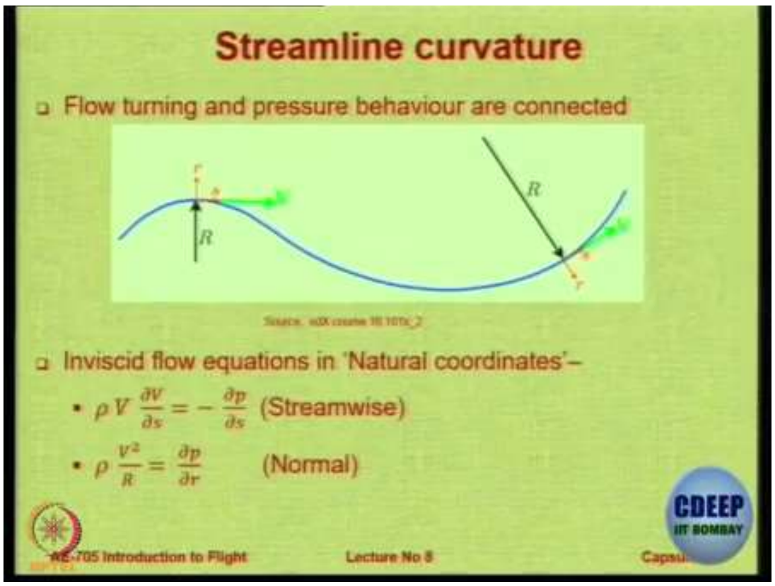

So, as per this particular explanation of stream line curvature, the primary point is that because of certain reason because of the presence of the body, if the flow stream lines undergo some turning and some curvature whatever be the reason, presence of the body in free stream causes change in the curvature of the streamline. So, we are going to look at a concept where presence of the body in the flow stream has let to change in the stream line curvature and whenever it happens in flow then, two important equations come into play.

Ok so if you look at inviscid equation ok, I am calling it inviscid equation because I want to right now neglect the viscous effects, ok. Viscous effects are actually more predominant when you look at creation of drag or the numerical value of drag. So, along the stream wise direction that means along the direction s, so the flow particle which moves along this curving stream line. So do you agree that if I remove the body the stream lines are straight ok, in assuming a steady flow and when

I bring the body then something happens because of which stream lines undergo some change in curvature. So if they undergo change in curvature the reason for that is a presence of the body.

So the presence of the body in the flow stream has caused change in curvature, if the change in curvature happens if and only if it happens then we have to look at the inviscid flow equations both along the stream wise direction that means the S direction so, the flow particles has a velocity V, as you know the stream lines are always drawn along perpendicular to the local flow velocity. So, we have a velocity V along the direction S which is the stream line direction and we also know the direction R which is perpendicular to the stream line direction called as a radial direction. So you can apply equation and you can get this particular value

$$\rho V \frac{\partial V}{\partial s} = -\frac{\partial P}{\partial s}$$

which is along the stream wise direction.

And along the normal direction

$$\rho \frac{V^2}{R} = \frac{\partial P}{\partial r}$$

which is the something like when you have a body moving along the curvature, you have on that some kind of a force acting called as centrifugal force is acting on it correct. So, that is Rho V square by R and that is the function of the change in the pressure in the radial direction so in the normal direction.

So these two equations we have to keep in mind right now and now we have to now apply to them apply to the flow field, whenever we have any curvature. So I am replacing once again reproducing the equation, $\rho V \frac{\partial V}{\partial s} = -\frac{\partial P}{\partial s}$ along the streamline direction.

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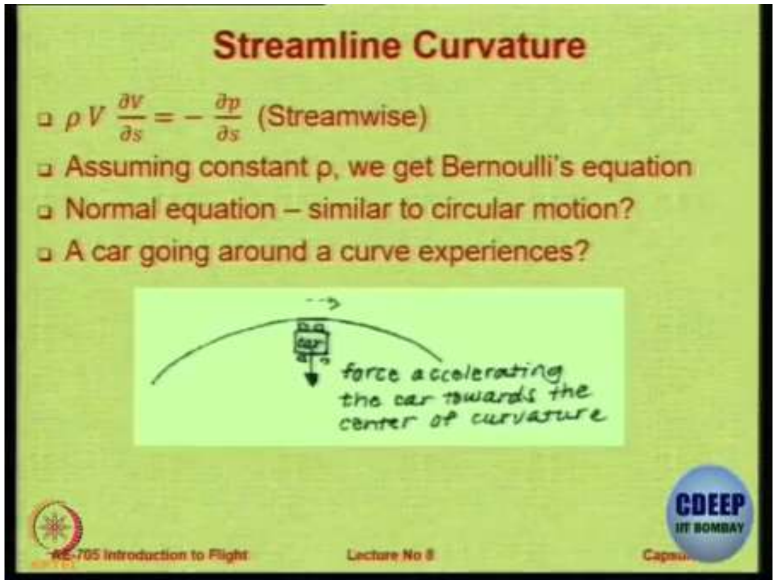

Notice that if I assume Rho as constant, if I assume and you know condition Rho is constant, we get the Bernoulli's equation ok. So this is nothing but the Bernoulli's equation in the incompressible domain. Now, the normal equation which I showed you this is similar to the circular motion whenever the body goes along a curvature which undergoes those forces. For example, if there is a car that is moving along the curvature then the car experiences some force $m\frac{V^2}{R}$ along the centre of the curvature. Similarly, a fluid particle is going straight on the stream line there is no curvature. Now you bring in the body, whether you bring it in flat plate or symmetric aerofoil or unsymmetrical aerofoil or thin aerofoil it does not matter. If because of the presence of the body there is going to be a change in curvature, there is going to be a force acting radially and the magnitude of this force is going to be directly related to the rate of change of pressure.

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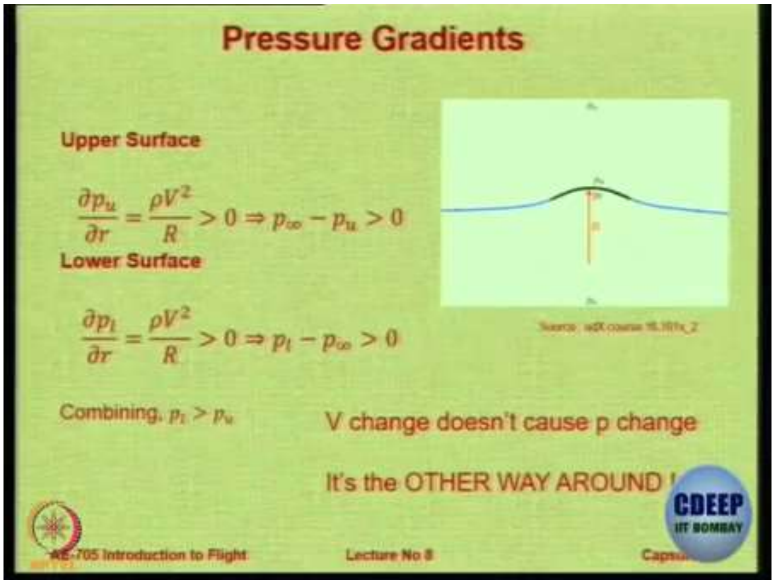

Ok so basically what is happening is suppose you have fluid with the pressure P_∞ at the top and bottom and you introduce this small shape this curved flat plate with some curvature R. So there is some pressure P_L lower below the body and there is some pressure P_U above the body ok. So on the upper surface, the partial variation of the pressure with R is equal to $\rho \frac{V^2}{R}$ and because R is non zero because there is some positive curvature R therefore, $\rho \frac{V^2}{R}$ is non zero. So, if $\rho \frac{V^2}{R}$ is non zero that means that the value of $P_\infty - P_U$ is more than more than or equal to zero, more than actually not equal to zero. Therefore, $P_\infty$is more than P_U ok that means the pressure on the upper surface is lower than that in the free stream, ok. Look at the lower surface, in the lower surface also you have some pressure P_L and in the area below the curved body

$\frac{\partial P_L}{\partial r} = \rho \frac{V^2}{R}$, again it is non zero because the value of R is non zero ok. So therefore there also you have $P_L - P_\infty$ is more than zero. So, if P_∞ is more than P_U and P_L is more than P_∞ then you can always say that P_L is more than P_U, ok.

So, if P_L is more than P_U there will be a pressure difference across the body and that is going to create a force on the body. So, interestingly so the velocity change does not cause pressure change in fact, the pressure change causes velocity change so, the argument actually is reversed.

So in short what is happening is, presence of any body that leads to streamline curvature creates a pressure difference and that pressure difference is both above and below the body ok. So now the bottom line is, lift will be created if and only if there is going to be some change in the curvature of the stream lines when the body is introduced, and the direction of this force will be up or down, depending on in which direction the curvature is created. If you have equal creation of stream line curvature above and below such as a symmetric aerofoil then the net lift will be zero because the top half will give one force and bottom half will give exactly equal and opposite force so, the net force will be zero.

So, from now on if you apply this particular principle of stream line curvature, the first thing you will look for is, when you brought in the body was there any change in the stream line curvature? If there was, calculate it along each stream line, and then you get the value of the net force that is created. Second thing is that in general what you can assume is that the transfer of momentum of the free stream flow that occurs on the body is also explainable by curvature effect, because of the transfer of momentum if the stream line does not get curved, then you may not get a lift. So the bottom line is if you look at the flow pattern so let us go back now.

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Look at this picture whether lift is generated or not does not depend upon the shape of body only, it only depends on whether this particular stream line does it undergo a change in the curvature or not. Similarly, here do stream lines undergo change in curvature or not? Larger the change in the curvature larger will be the $\frac{\partial P}{\partial r}$ and that will give you the value of the force created in any direction, depending on the situation ok. So this particular system or this particular approach can easily explain the phenomenon of producing lift. I will again repeat, if there is no change in the stream line curvature there will be no lift, if there is change in the curvature there will be lift.