Introduction to Fluid Mechanics and Fluid Engineering
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Lecture - 44
Flow Past Immersed Bodies (Contd.) and Sports Ball Aerodynamics

We have been discussing on flow past bodies various shapes and if we recollect that in our previous class we identified that there could be bodies of different shapes, which are generated out of considerations of various elementary flows if you start with a potential flow consideration. May be one of the important things of concern for such cases is that if you have a wall or if you want to represent the existence of a wall how do you represent that?

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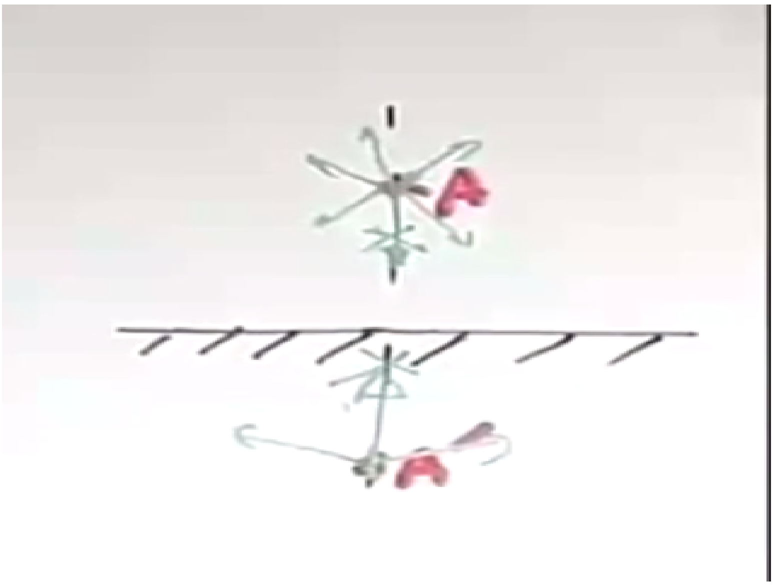

For example, say you have a wall like this and say you have some source located at this point say A which is basically on the y axis where wall is the x axis. So you have a source of a given strength located at A, wall is not given to you, say only the location of source is given to you. Now you are told that now we have a wall, we should have a combination of super position of flows which would represent the effect of this wall.

So how do you do that? Given this source is already existing. We have to keep one thing in mind what is that? We are talking about a potential flow in this example, when we are talking about a potential flow it means that no penetration boundary condition is the only boundary condition that we have to satisfy at the wall. So if you have a source like this, see the source radially emits flow in all possible direction.

That means it also emits a flow radially in the downward direction. Now from this do you have a clue that what we should do to make sure that there is 0 normal component of velocity at the wall? No, phi=0 or rather stream line or a stream function=0 represents a body of a particular shape because the surface of the body is a reference stream line that is true but how do you ensure that with this physical example.

What more you have to get to ensure that yes this is such a line where you have no penetration. So it is the inverse problem. It is not that you generate a body of a given shape given a body or given a wall what extra thing you need to have with this to ensure that you satisfy no penetration at the wall. Let us say this is a plain wall just as an example. Just think like this, it is a very common sense thing.

Say you have just like a reflection you have image source located at this point. So if you have an image source located at this point see that it will also have its own radially diverging field and one of the velocity directions is this I mean it will be perpendicular to the wall. So if these 2 sources are of equal strength and located at equal distance from the wall, then these 2 effects will nullify each other to have resultant normal component of velocity 0 at the wall.

So this is a very simple concept but maybe implemented in practice very easily. So it will now become a superposition of a particular say source and an image source where the image is with respect to the deflection as if the wall is like a mirror. So a superposition of that so this is known as method of images, very convenient method and one can generate the effect of the wall using this.

Now we have also discussed that not all flows are potential flows in fact no flow in reality is the potential flow but potential flows are important because if it is a boundary layer theory that you are applying then outside the boundary layer you may apply the concept of potential flow and whatever pressure gradient that you calculate out of that the same pressure gradient is imposed on the fluid within the boundary layer.

But because of the existence of the boundary layer, you have the viscous effects also important and that dictates what should be the drag force on a body. Of course if you have very high Reynolds number flow and a bluff body or a body of such a shape that flow separation occurs quite quickly then the form drag or pressure drag remains to be the more important concern than the skin friction drag.

And then the drag coefficient sort of may become independent of Reynolds number at a very high Reynolds number. Now if you have say a flow where viscous effects are important then you represent that with a drag coefficient where the drag coefficient is the combination of the skin friction drag and the form drag or pressure drag. Now the drag coefficient will have in general a dependence on Reynolds number.

In certain cases, for very high Reynolds number flow because the form drag effect is very important, so it may become virtually independent of Reynolds number but otherwise because of the skin friction effect it becomes a strong function of the Reynolds number otherwise. So let us look into one or 2 problems where we illustrate or we try to see that what are the consequences of that.

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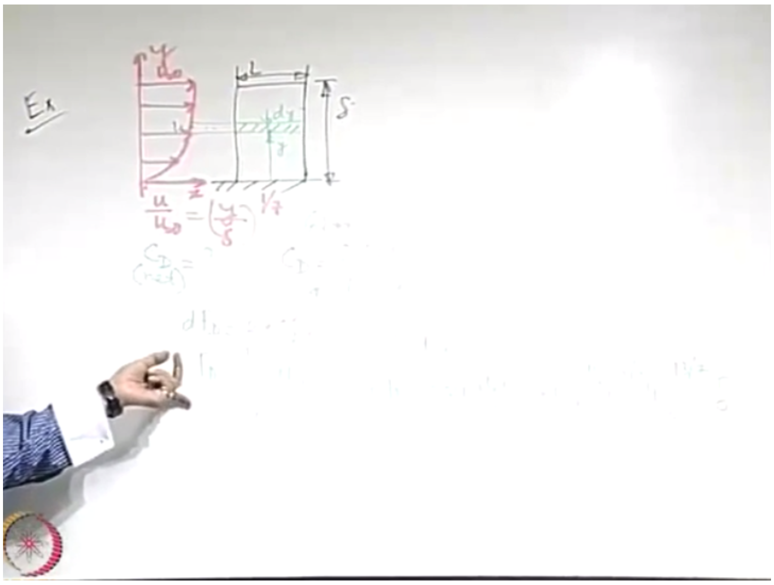

So let us consider one example say you have a flat plate but this plate is oriented in a bit of a special way, the dimension of the plate is given. The dimension of the plate is given as the height is delta and the width is L and you have a free stream velocity. The free stream velocity is not a uniform velocity but the incipient stream is like a boundary layer already developed by itself.

And assume that this is a turbulent boundary layer where you have the velocity profile given by u/u infinity=y/delta to the power of 1/7, this is given. You have to find out that what is the total drag coefficient of the net drag coefficient because of the interaction between the fluid and the solid plate. What is given is that for a turbulent flow you may assume that the CD is 0.031/rho uL/mu to the power 1/7 that is given.

This is the CD based on a local velocity, this is the CD net that is the net effect on the plate what is the equivalent CD that you have to find out okay. So to find out the CD what you require? You require to find out what is the total drag force. So to find out what is the total drag force which is there acting on the body how you should go about it. See if you take a thin strip say at a distance y you take a thin strip of width dy.

What is the drag force that is acting on the strip? See why we are taking such a strip because we want to use our knowledge of boundary layer for flow over a flat plate. For flow over a flat plate which is oriented just instead of this say oriented in such a way that a uniform flow is flowing on the top of that then the reference drag coefficient is based on uniform u infinity. Here as if the u infinity which is coming on the top of this plate is varying.

It is varying from 0 to u infinity as you are moving along the height of the plate. So if you take a small strip over which the local u infinity is the local u. What is there what is this u? So then if you calculate that what is the local drag force, the local drag force is the local CD*1/2 rho local u square*the area L dy. Of course, in practice if it is a slender plate like this fluid is flowing on both the front and at the back.

So you may multiply this by 2 for the 2 sides and you can substitute CD as the function of u and the total drag force you may integrate dFD from y=0 to y=delta and u as a function of y is given. So that you have to substitute for doing the integration. So I am not going through all the integration, but if you calculate the total drag force it is 0.031*49/62*rho nu to the power 1/7 L to the power 6/7 u infinity to the power 13/7*delta.

This is the final answer to this problem and of course the net CD is something which is artificial. What is more important is the drag force because you may just use any reference velocity say you may use the reference velocity as u infinity and very easily find out the CD by the drag force/1/2 u infinity square*delta*L is the area of the plane but important is what is the drag force effectively that is what is more important.

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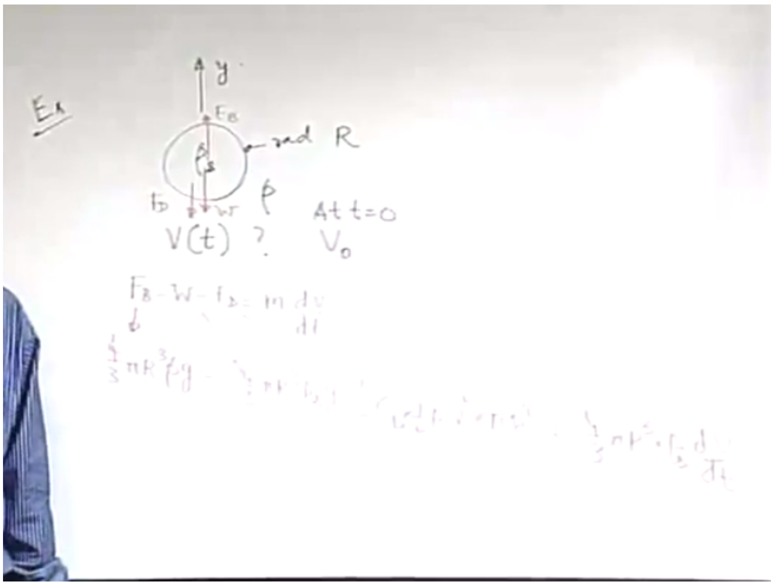

Let us workout another problem. So you have a sphere which is moving in a liquid. The sphere has the density as rho s and the liquid has the density of rho. The radius of the sphere is R. So you have to find out how the velocity of the sphere varies as the function of time if it starts from a velocity V0 at time=0. Assume that it is moving in the vertical direction okay. So now if you see just if you consider the free body diagram of this sphere.

So what are the important forces that you see on this sphere? So if you draw the free body diagram you have the weight, you have the buoyancy force and drag force. So if it is tending to move upwards the drag force is trying to make it move downwards. So when we say that when the sphere is tending to move upwards, it means relative to the fluid. That means it might be so that the sphere is stationary.

But the fluid is moving downwards from the top it is all the same but when we are writing equation of motion for this sphere, we are writing its velocity as velocity of it relative to the fluid that means as if the fluid is stationary. So if it is moving upwards relative to the fluid then you have the drag force. So you have the buoyancy force-the weight-the drag force=the mass of this sphere*dv/dt that is the Newton second law right.

So these things the buoyancy you can very easily write what is the buoyancy? 4/3 pi R cube*rho*g-4/3 pi R cube rho of this sphere*g drag force. It depends on the relative velocity that is what is important. So you cannot say what it is, you can just write it as say CD*1/2 rho v square*the reference area. So that is pi R square right. Again the projected area is the reference area for these cases, so not 4 pi R square that you have to keep in mind.

So that is equal to 4/3 pi R cube*rho of this sphere*dv/dt. So the whole attention now is that what is the CD right and that depends on the Reynolds number of flow. So this is the function of Reynolds number. If the Reynolds number is very, very low, say Reynolds number<1 then the Stokes law is approximately valid. So if Reynolds number is much, much<1 you have the CD is 24/Reynolds number based on the diameter of this sphere.

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And there will come another velocity. If on the other hand Reynolds number is very, very large, very large Reynolds number, CD may be approximately a constant independent of Reynolds number because at very high Reynolds number, we have seen that the effect of the form drag for bodies with curvatures become more and more important and the reason is as you say as you increase the Reynolds number what happens?

What happens with the boundary layer? Boundary layer becomes thicker or thinner? If you increase the Reynolds number, the boundary layer becomes thinner. So when the boundary layer becomes thinner then when the surface effects of the fluid at there then are penetrate into the outer fluid outside the boundary layer and they may part a bit sufficiently and that of course it becomes more and more important.

So form of the geometry of the surface tend to become more and more important as you increase the Reynolds number. Now at very large Reynolds number CD is approximately constant independent of Reynolds number.

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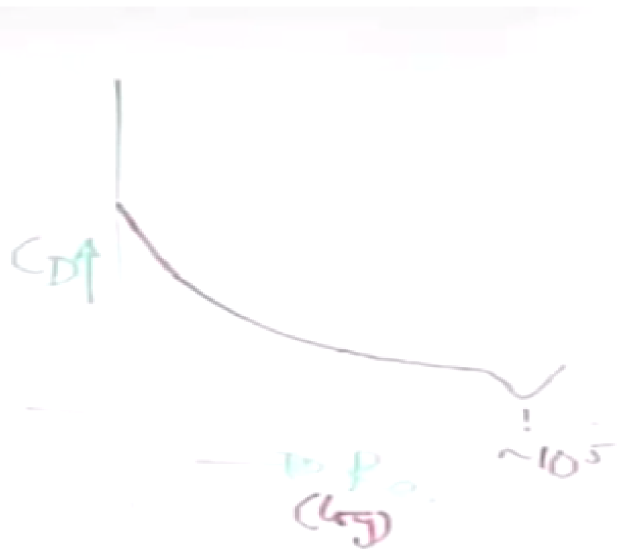

So if you draw say CD what is its Reynolds number for flow past as sphere? So what we will get out of this? So what you get is something approximately like this. So let us say we plot with the log of Reynolds number. So CD=24/Reynolds number if you plot it as a log of Reynolds number, it will be like a straight line but that is valid only for very low Reynolds number. Then there is a significant deviation from this and so it will come down like this.

And there will be a sudden transition at a particular Reynolds number when the CD goes down. Before this transition, the CD was approximately as the constant, so it is not really an exact constant but it is almost like an asymptotic like it is almost approaching a constant. Then suddenly there is a transition again it increases. This is roughly say for a sphere maybe it is of the order of 10 to the power 5 this Reynolds number.

Now what happens here? Here there is a transition to turbulence, because of a transition to turbulence what happens the boundary layer separation is delayed. We have seen that like when the shape of the body is important in terms of the form drag, boundary layer separation is what matters because early separation will induce a lot of form drag but later separation will reduce the form drag.

So when the boundary layer becomes turbulent, the separation is delayed. So it reduces the form drag and since at very high Reynolds number form drag is what is important the reduction of form drag is what is prominent here but beyond that if you increase the Reynolds number further then many interesting things may occur because I mean it is a change of the state of turbulence from one state to another state where the point of separation again shifts more towards the upstream.

That is why this is all related to the boundary layer separation, so what we are trying to understand is that towards the high Reynolds number for flow past bodies with curvature, the boundary layer separation is the very important phenomenon that dictates the total drag force and the similar behavior is there for flow past cylinders and let us try to understand what happens for flow past circular cylinders as special example.

So we now look into some of the animated representations or movies related to flow past circular cylinders.

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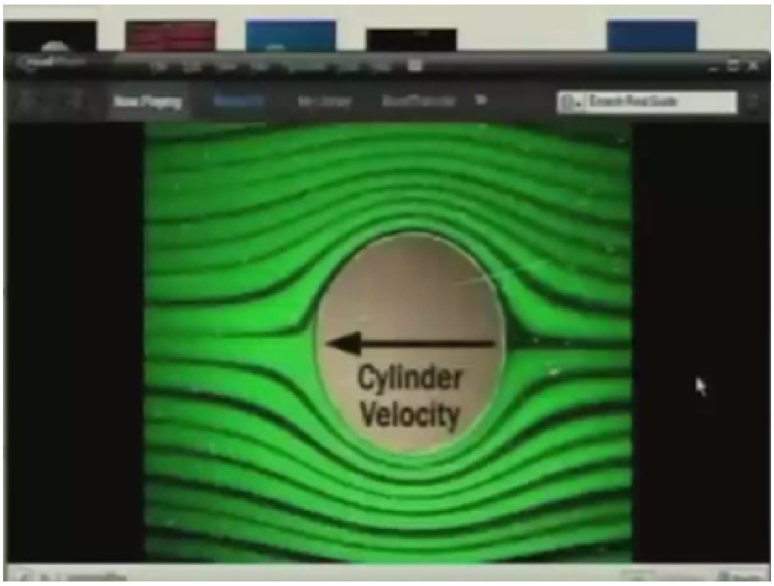

So one by one we will see and we start with a particular visualization where it is almost like a potential flow. So if you see that these green colored lines this represent sort of stream lines and if you see that these stream lines are very symmetrically coming from one side and they are also symmetrically merging in the other side the front and the back side. So almost a perfect symmetry is maintained so just like what a potential flow could predict.

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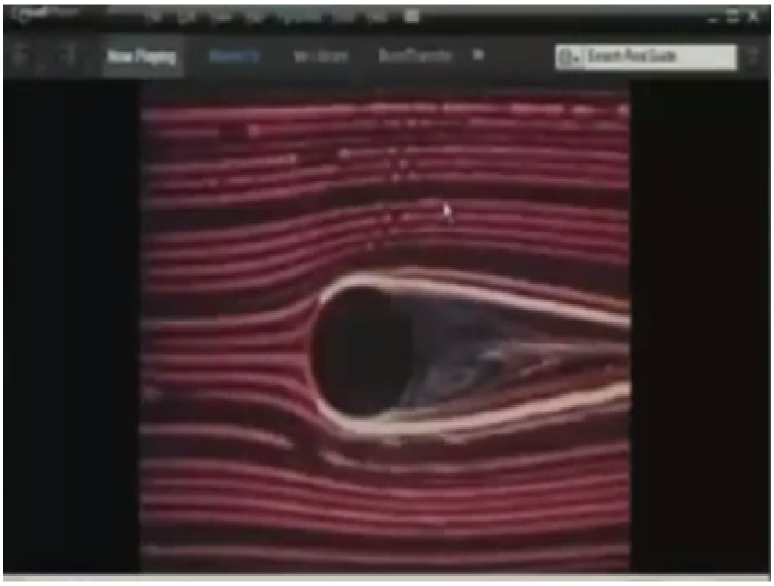

Now if you increase the Reynolds number what happens? So let us say that the Reynolds number is increased beyond say 4 or something like that. See at very low Reynolds number the solution is always like stokes flow solution. So the solution does not consider the fluid flow or the advection terms in the left hand side of the Navier-Stokes equation. So the advection effects are totally neglected in that solution.

But in reality the advection terms maybe important typically as you go for downstream and what happens is see physically what happens the wall is the source of vorticity because wall generates a cross velocity gradient and that vorticity is transmitted within the fluid. So if there is a strong advection then the advection transmits the vorticity from one place to another place and creates an asymmetry in the flow.

So if advection effects are totally neglected that asymmetry is totally neglected then vorticity is just diffused in all directions equally but if the advection effects are there then vorticity is preferentially transmitted or advected towards the wake side or the low pressure on the back side and what is the consequence? So whatever we showed as a visualization example.

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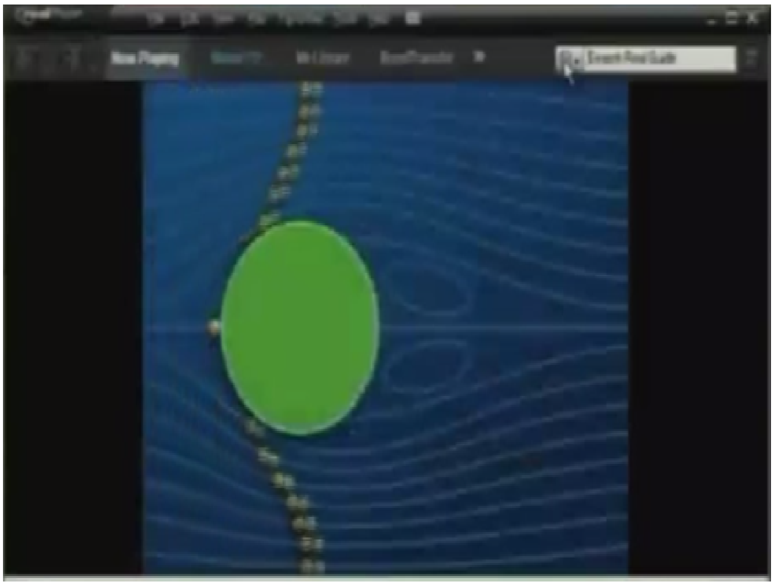

Let us see it as a simulated example. So if you see 2 Eddies of counter rotating nature are formed at the back or in the low pressure region or in the wake side of the cylinder. We are talking about still low Reynolds number cases.

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Now if you say increase the Reynolds number you see certain interesting things. So if you see these are like staggered vortices, which are forming so there is one row of staggered vortex interacting with another row of staggered vortex and these are sort of rolling in the opposite direction. So if we want to look into it in a bit more detailed manner. Let us try to look into another movie.

And with that movie what we will try to see is that what are the implications of these alternately rotating vortices?

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So these alternately rotating structures they have sort of an impression of footprints on a road and this was first observed by Von Karman and that is why this is known as Von Karman Vortex Street. So if you see that basically what is happening is these vortex streets or these vortex lines so to say are interacting with the small eddies the 2 counter rotating eddies which were formed close to the cylinder.

Because with increase in Reynolds number these vortices are coming very close to the back of the cylinder and they are interacting with those small eddies and so alternately you are having sort of staggered rolls of vortices rotating one against the other.

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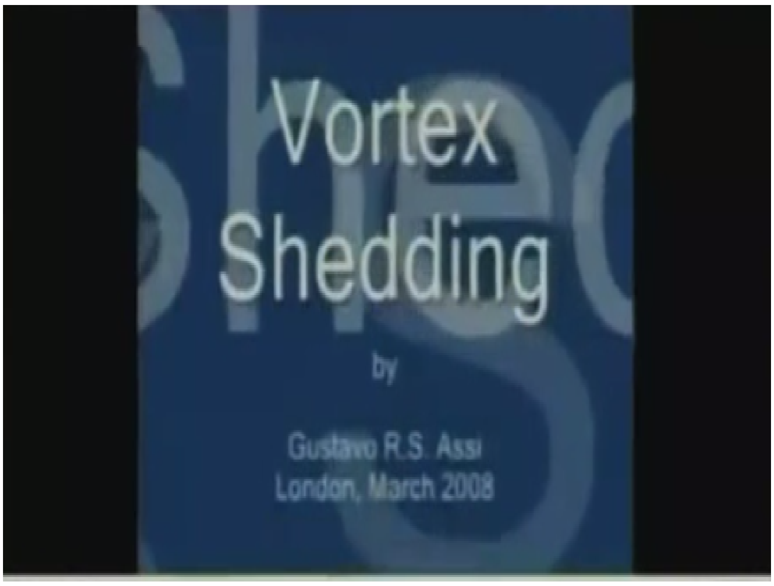

Now, so we will look into one interesting flow visualization of vortex shedding.

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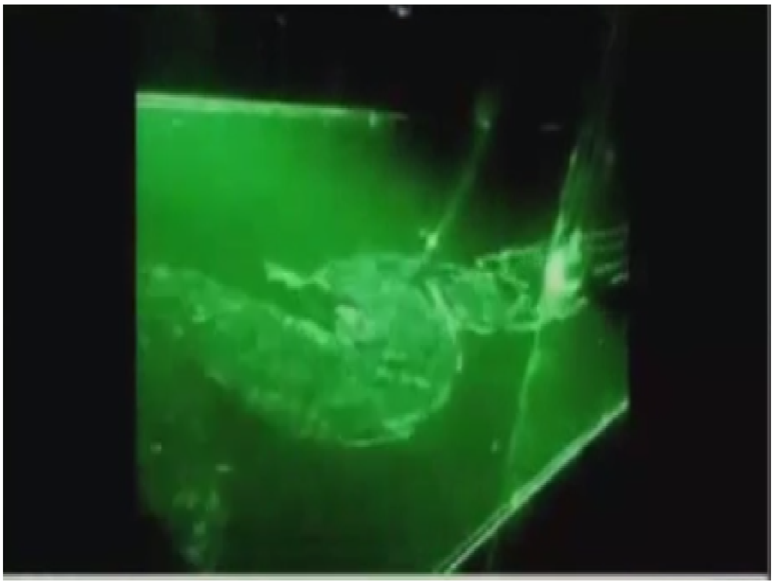

This phenomenon is known is vortex shedding.

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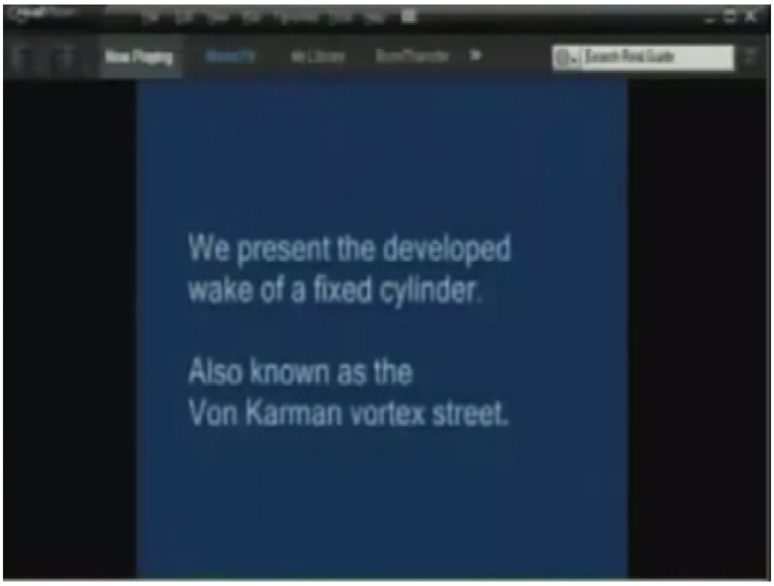

That is as if there is a flow past a cylinder, it is not just for a cylinder it could be for body of any similar shape but cylinder is just a demonstration.

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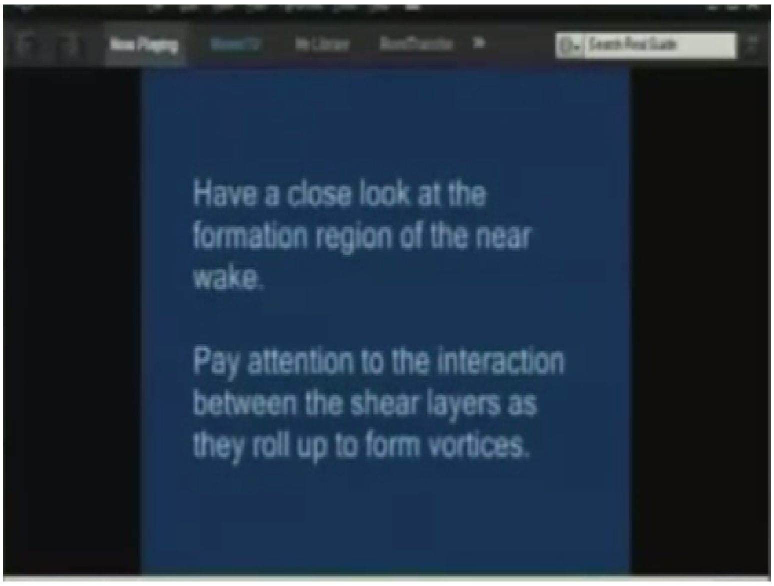

So what we want to see first before going into the phenomenon of vortex shedding in more details that what types of vortex rolls are formed in the back of the cylinder, so in the wake region or the low pressure region. So like animated description of the Von Karman Vortex Street.

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So just look into this very carefully because this gives you an idea that what sort of vorticities are there not in a quantitative sense but at least qualitatively what is the nature of rotation of this individual vortices and these vortices may be of quite complicated nature.

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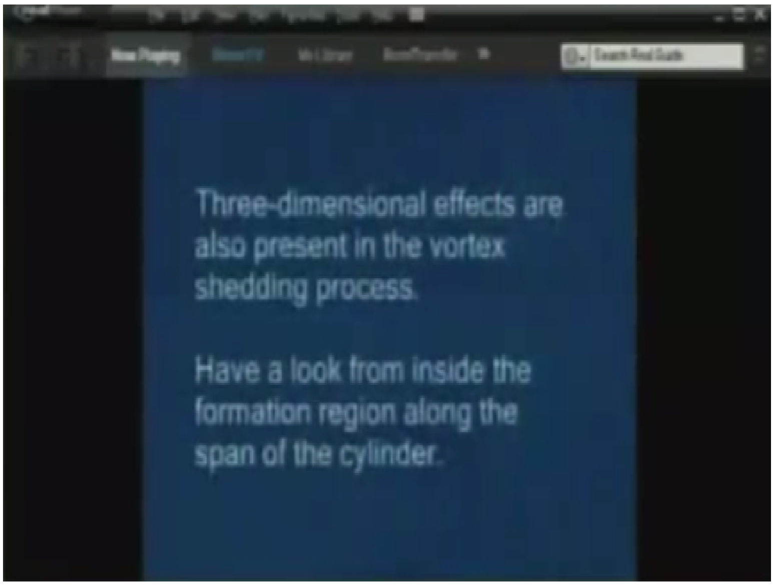

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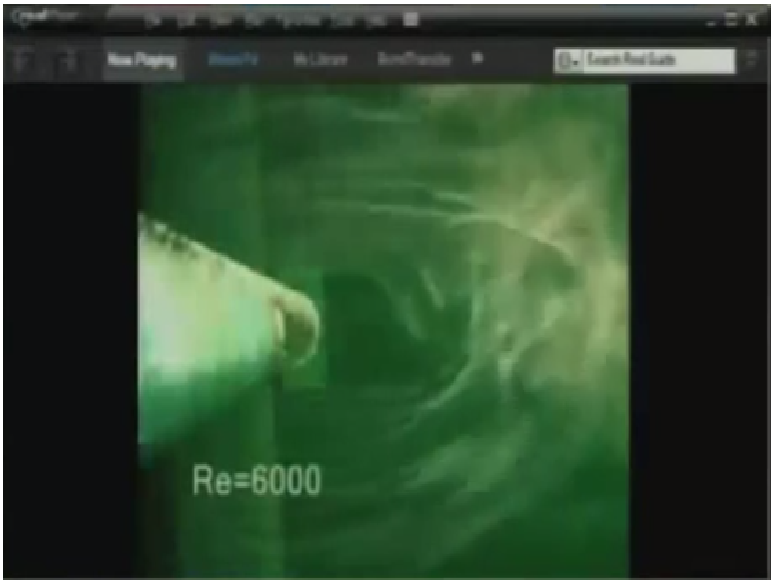

And one of the important things that comes out of this experiments is that although the flow that came towards the cylinder was steady but there is an unsteadiness in terms of appearance and disappearance and the frequency of the rolls which are appearing.

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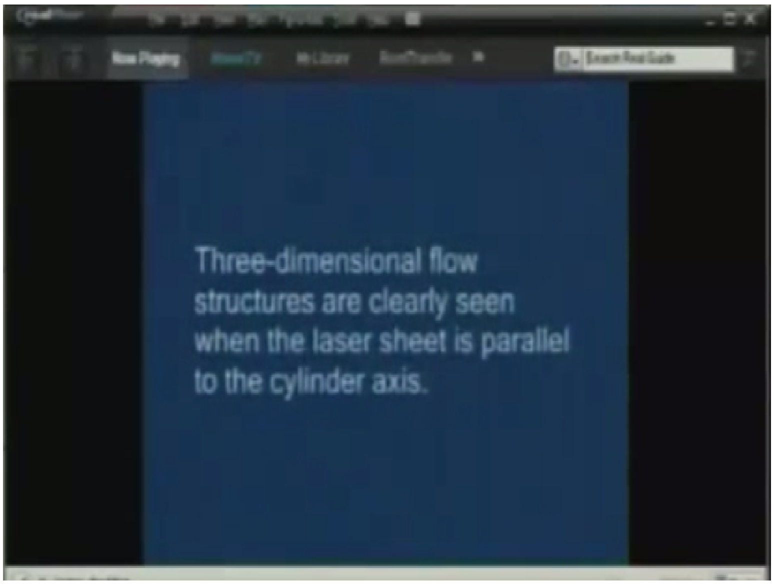

So although the incipient flow is steady but flow at the back of the cylinder is unsteady and it has a sort of a frequency or it has a sort of a periodicity in terms of the happenings. That is the vortices are appearing disappearing again appearing disappearing. So vortex of one particular directional rotationality is appearing, then vortex of an opposite rotationality is appearing.

And the previous one is disappearing, so alternately vortices of opposite signs are appearing and disappearing and this phenomenon is known as vortex shedding and is one of the very important phenomena that you can see in flow past bodies of these shapes.

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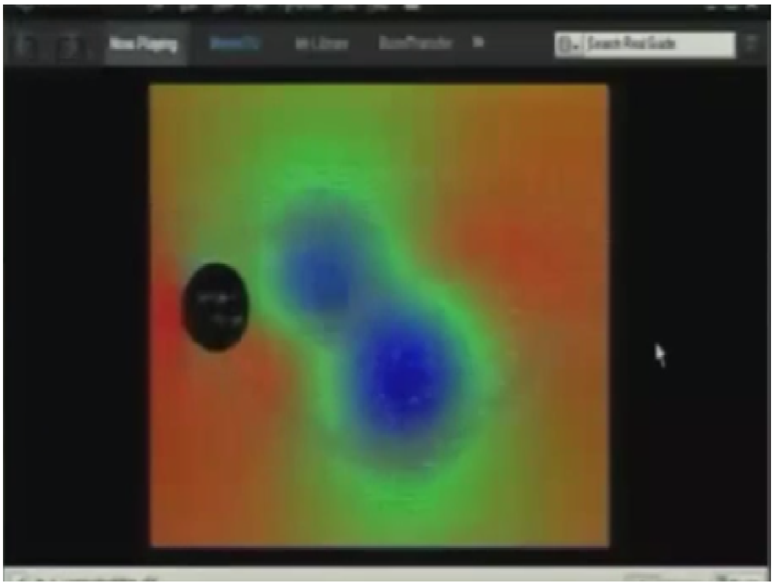

Now you can generate these types of flows in using computational techniques also and this illustration will give you an idea of like how the vortices of different rotating nature are shed from the cylinder as if they have been shed from the cylinder towards the fluid. So you can see this clearly from this illustration. Now we will see some more examples of the vortex shedding.

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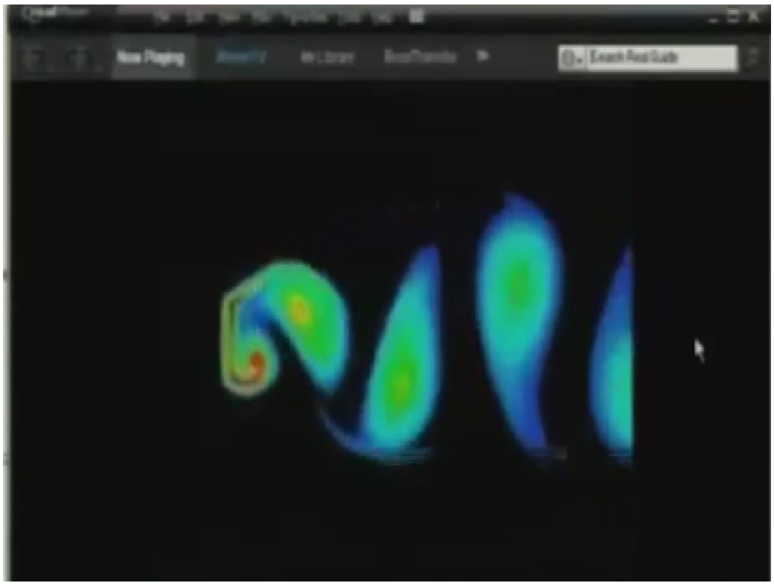

This is also an animated description, you can see that are like alternating vortices are shed in the fluid from the cylinder and that occurs for quite a large range of Reynolds number and it si important for many reasons because we will see through one example that what effect it has on the cylinder itself.

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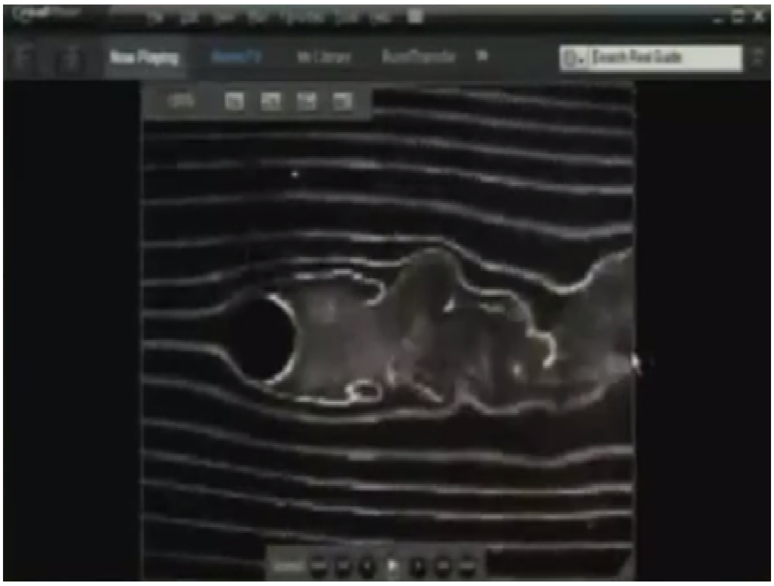

So with the width of the higher Reynolds number, this oscillation frequency where this also changes and we may have different experimental visualizations of these ones.

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So this is one experimental visualization unlike the computational visualizations that we saw in some of the previous examples. This is an experimental visualization of the same thing. So we are just trying to look into this vortex shedding phenomenon from different visualization perspective.

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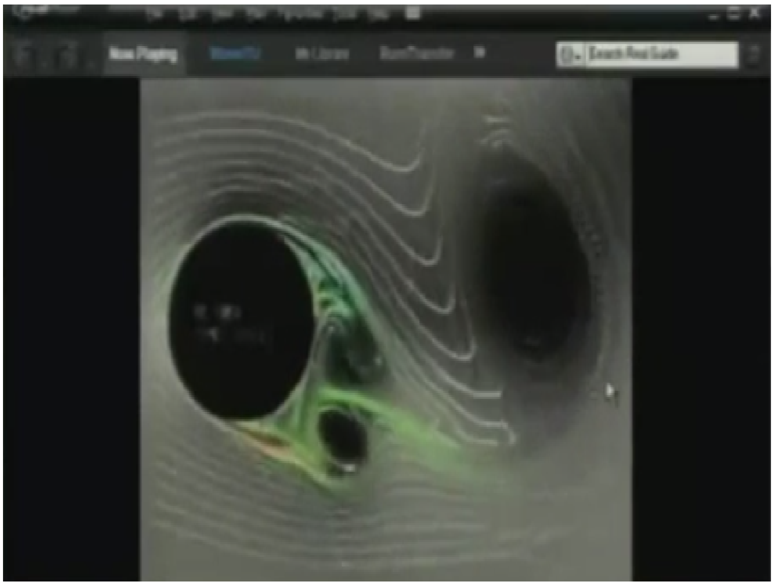

This is a computational way of like generating the similar type of behavior and you can see from this example clearly that these vortices are as if rolling upwards and downwards, upwards and downwards like that and that creates an alternating sort of frequency in the flow.

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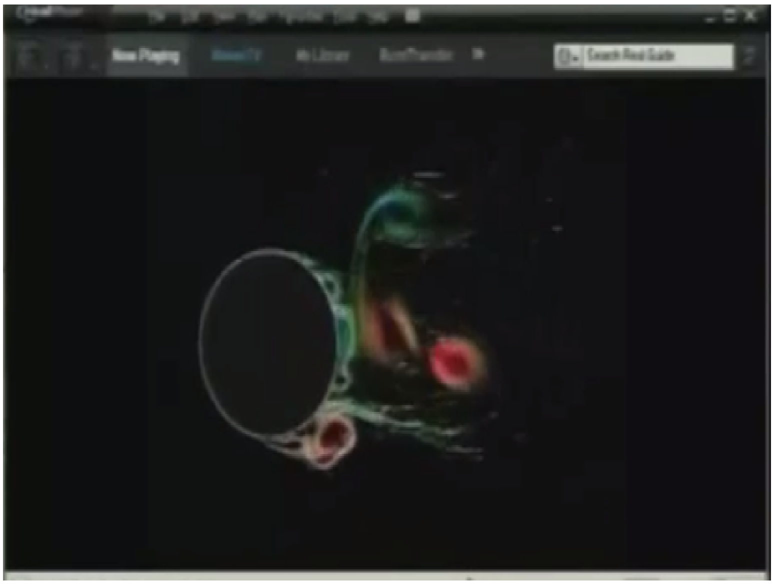

So this is a flow itself is inducing some nature of rotationality or some nature of frequency in the system and if you see that because of this sort of transience in the flow, the cylinder may itself start oscillating. So this is called as flow induced vibration of the cylinder. So it was a steady flow, it was not an unsteady flow, so if something vibrates because of unsteadiness in a flow that is intuitive but here the flow that was incipient to the cylinder was steady.

But because of this physical phenomenon of vortex shedding, you are now having some phenomenon which is occurring with the frequency and that is forcing the cylinder to oscillate and it may be very critical if that forcing frequency becomes same as the natural frequency of the cylinder because that can give rise to very high amplitude and sort of resonance.

And that is one of the important consequences that may occur in a very strong fluid structure interaction.

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So you may have even multiple cylinders and with multiple cylinders these types of effects you can see with like as if one effect is getting superimposed on the other. Here the symmetry sort of is very well preserved because the Reynolds number is not that large but the symmetry may be destroyed by advection of vorticity if the Reynolds number is substantially larger.

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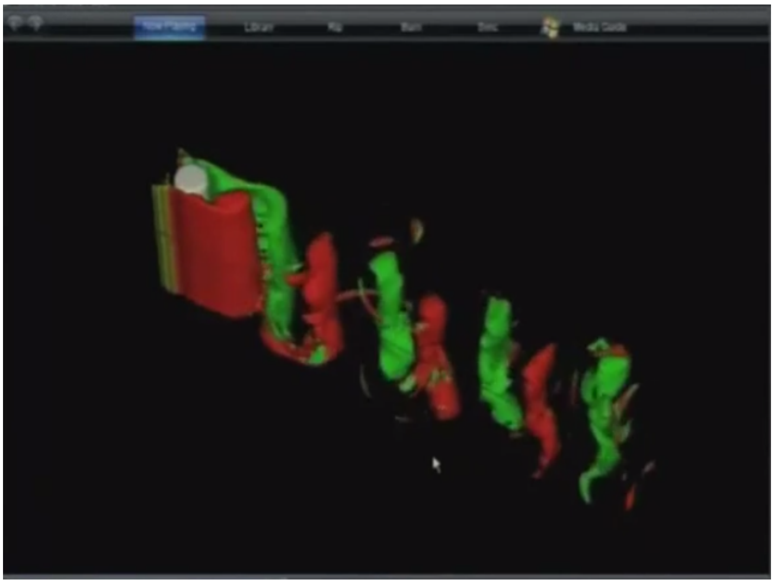

Now if you want to look it in the form of a 3-dimensional structure so you can see that by the example that we will be seeing here, let us try to see this example, may be we just play it again okay. So if you see this is a 3-dimensional structure, so here the vortex shedding phenomenon is shown in 3 dimensions but the basic phenomenon is very, very similar to the 2-dimensional flow visualization observation that we have seen.

Now if you want to say see the behavior so these like the vortex shedding frequencies are very, very critical for the design of a say structural system and it may be possible that there is a wide range of Reynolds number to which the flow is subjected so if you want to look into the flow past a circular cylinder, we could see that first there were some small vortices which were formed close to the back of the cylinder.

Then these vortices almost periodically appeared and disappeared and interacted with the main flow and created a vortex shedding phenomenon. Now if you increase the Reynolds number to a very large value then beyond a critical Reynolds number, which is roughly like maybe of the order of 5*10 to the power 5 or so, there may occur a transition to turbulence.

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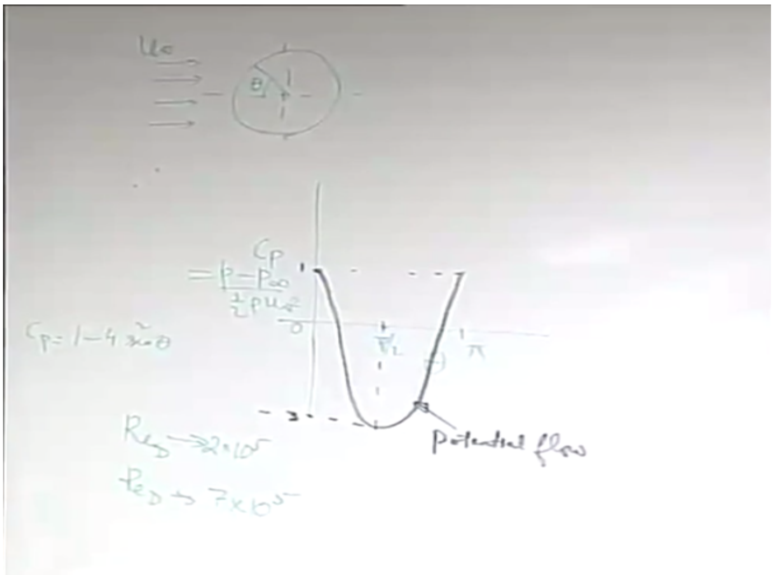

So if you want to plot the pressure distribution around the cylinder, so when we plot a pressure distribution we basically plot the Cp versus theta so Cp is the pressure coefficient p-p infinity/1/2 rho u infinity square. So the physical situation that we are considering is there is the circular cylinder and there is a flow past this circular cylinder. Flow is coming with the velocity of u infinity.

And theta is a sort of angle measured with respect to the incipient flow. Now let us try to make a sketch say from theta=0 to theta=pi, the variation of the coefficient of pressure which is basically a non-dimensional variation of pressure as a function of theta. First of all, let us plot it for a potential flow. So for the potential flow if you recall that it was 1-4 sin square theta for flow past a circular cylinder without any rotation.

So if you want to make a plot of this say this is pi/2 and this is pi. So when theta=0, this is=1. So let us say this one when theta=pi/2, it is -3 so let us say may be this one, so if you make a sketch of it like this and then when theta=pi 1 again so something like this okay. So this is potential flow solution when will the potential flow solution be valid in terms of pressure distribution?

If there was no boundary layer separation, then it would have closely followed this because whatever is the pressure that is imposed from outside the boundary layer same pressure distribution the boundary layer is supposed to feel so long as the boundary layer theory itself is valid that is so long as there is no boundary layer separation but if the boundary layer separation has occurred.

Then so if the boundary layer separation has occurred so it all depends on whether the separation is early or late and for that let us consider say 2 Reynolds number one is Reynolds number, these Reynolds number are based on the diameter D of the cylinder. So Re D. Let us say one value we take as say 2*10 to the power 5, another Reynolds number we take as say 7*10 to the power 5.

And let us say in between there was a transition, so let us consider that 2*10 to the power 5 is the laminar case. So if it is a laminar case let us try to make a plot of that so if you compare these 2 in which case there will be earlier boundary layer separation, in the first case right because the turbulent boundary layer has a greater momentum to sustain the adverse pressure gradient so its separation will be delayed.

So we expect usually that the separation will be there in the region where the adverse pressure gradient is failed. In reality in the region where there is an adverse pressure gradient that is failed there occurs a back flow and the effect of the back flow is propagated even a bit in the upstream direction. So that the separation in the practical case for a flow of this Reynolds number regime occurs at roughly theta=82 degree.

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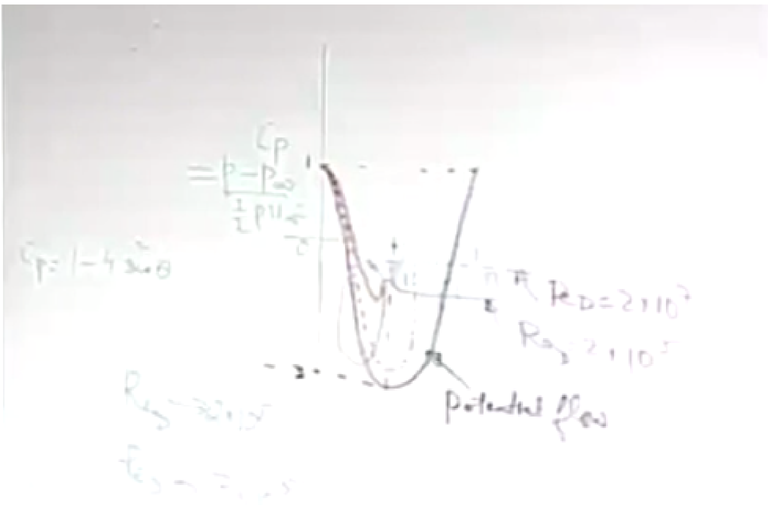

That is the practical observation. So till the separation has occurred maybe it will not show a lot of deviation from the potential flow theory but as it comes to a separation it will show some sort of deviation from the potential flow theory. So this is Reynolds number=2*10 to the power 5. See after the separation has occurred, the Cp is roughly a constant.

That means the pressure in the low pressure region or the wake region after which the boundary layer separation has occurred is almost like a uniform pressure which does not change further with theta and it is typically a low pressure region. When it is 7*10 to the power 5 say it is beyond the critical limit or the threshold limit. So then the separation will be what?

It will be further delayed and typically these separations may occur close to 120 degree or something like that maybe 118 degree this type of angle and till that limit so if you draw that line so till that limit it will follow very closely the line, which was there for the potential flow solution and then when there is a flow separation, it will come to a constant Cp which is independent of the angle theta.

That is the constant pressure in the wake region is almost like a constant. So this is Reynolds number=2*10 to the power 7 and these angles are like roughly for the angle from which this change of behavior is observed depends on the separation for laminar close to 80, 82 degree maybe for turbulent close to 120 degree something like that. So you can clearly see that depending on whether the boundary layer is laminar or turbulent you have a different pressure distribution right.

And this all is because of the different points of separation, so that means if you have on one side of the cylinder a laminar boundary layer, on another side of the cylinder a turbulent boundary layer because of their difference in the point of separation, you might have different pressure distribution on the 2 sides and that is what is the very important understanding that we get out of that.

It is not only true for a cylinder, the similar behavior is also true for a sphere and because of this difference in pressure distribution maybe around the 2 sides of a sphere because of maybe the boundary layer is laminar in one side or turbulent in another side. It is possible that this sphere experiences a lateral force.

So if it is a ball it starts swinging because of that and we will try to now see that how the dynamics of the sports balls are associated with these sort of observations that we had till this time. So let us look into some examples related to sports ball dynamics.

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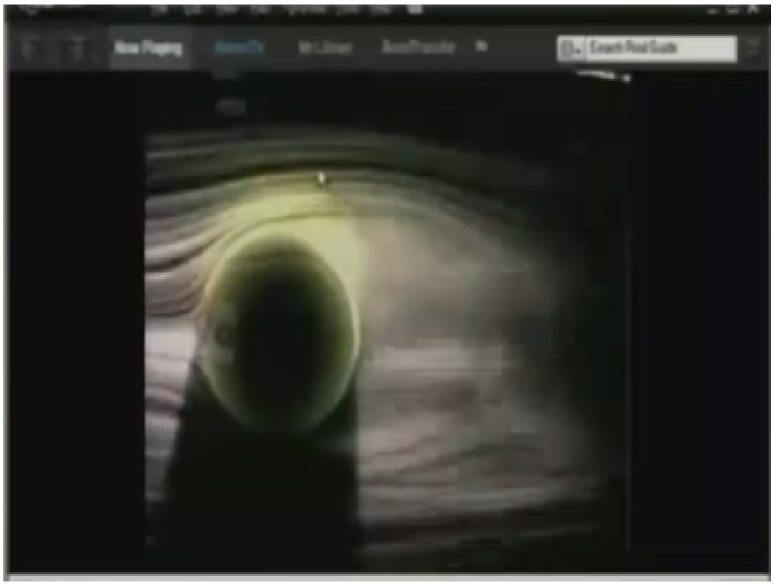

So we start with an example of a tennis ball. So let us say that there is a tennis ball which is being tested in a wind tunnel. See if you want to test the behavior of say pressure distribution around a ball you may have the ball stationary and the air flowing past it because what is important is the relative velocity between the ball and the air. In reality, the actual motion is the other way because you throw the ball and the ball is moving in the air but here you are keeping the ball stationary and blowing air past it.

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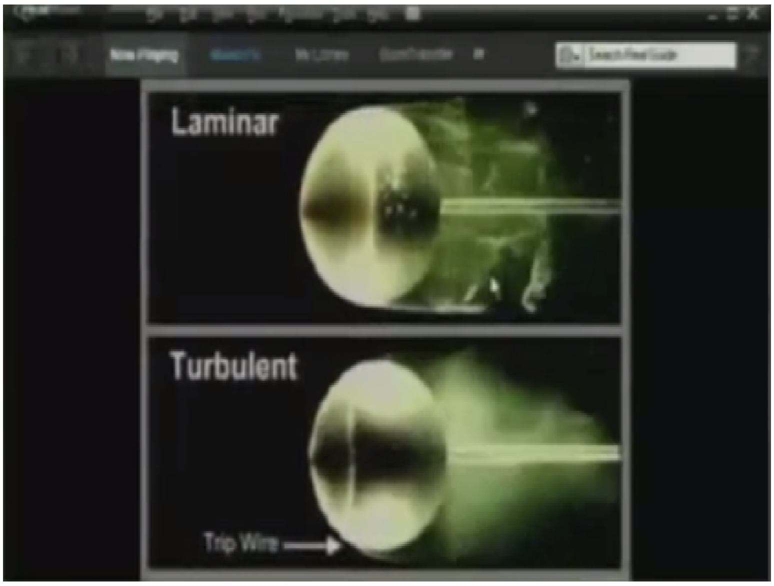

So if you want to see that you now compare the flow past similar tennis balls one with the laminar boundary layer, another with a turbulent boundary layer and you can clearly see that in the laminar boundary layer because of the early flow separation, there is a large wake or the low pressure region that is formed with a sort of rotating structure of flow in the back. In the turbulent boundary layer that separation is somewhat delayed.

And you do not have such a large wake region so that gives rise to a different kind of pressure distribution in these 2 cases.

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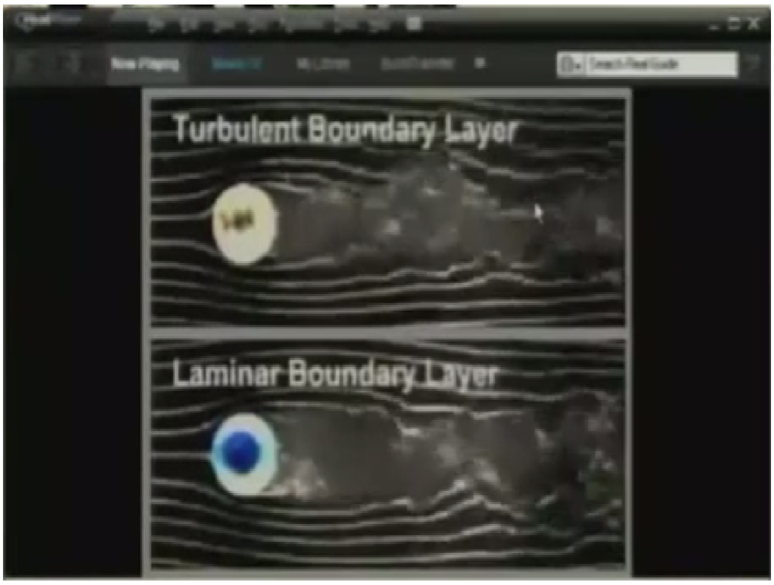

So these are examples with base balls and even the similar types of phenomena they are applicable.

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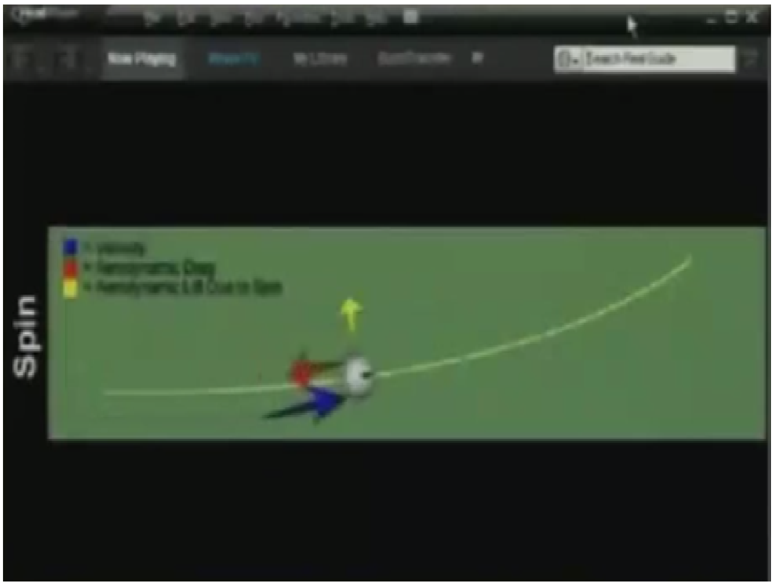

Now if you see in terms of the rotation, now rotation of a ball, it will depend on unlike the lateral of the side force which depends on the drag force I mean here it many times may depend on a lift force, not always but in certain cases because we have seen that if you have a body of a given shape and if you have a vortex which is one of the important constituents that is generating flow past a body of that shape, then that will create a lift force.

And we could get an expression for the lift force as a function of the circulation and the free stream velocity and that applies equally to the sports balls as well because there is a lot of cricket that goes on in our country maybe we will spend a bit more time on how these cricket balls have different types of motions.

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So we will briefly look into the fluid mechanics of cricket ball swing. So the whole idea is not to like be very, very detail in how a cricket ball should swing. It is one of the very important and active areas of research but what is more important is to give a broad overview of whatever simple things we have learnt in our boundary layer theory and flow past bodies of different shapes.

Then how that maybe applicable to the movement of the cricket balls that we very commonly see in different matches.

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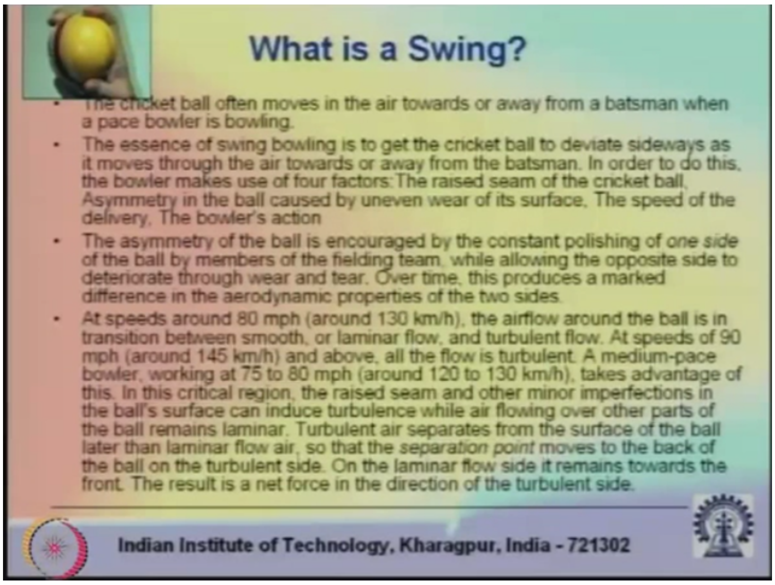

So I mean everybody knows what is a swing but let us just very briefly look into it. So swing is a sort of lateral movement of a ball right and this lateral movement is influenced by many things and we will see that what are the factors, which influence the lateral movement but what is important is to have a basic idea first of what is the effect of the speed of the ball on this lateral movement and that is very important.

Because we have intuitively seen that many of these phenomena are strong functions of Reynolds number and given the diameter of the ball as fixed, so the velocity of the ball relative to the fluid or in other words velocity of the fluid or the air relative to the ball is what is sort of important.

So I mean depending on the size of the ball it may be different so for the size of the cricket ball it is at speeds of around 80 miles per hour or roughly 130 kilometer per hour, the usual transition to turbulence may occur. So at speeds of around say 90 miles per hour, which is considered to be good speed of a fast bowler or 145 kilometer per hour. You will have the flow as turbulent.

Now the question is that if the flow is turbulent and it is equal in all sides of the cricket ball then it will generate and it is turbulent in the same way in all the sides. Then it will generate no resultant sidewise thrust or sidewise movement. So what may be important in one case say with the brand new cricket ball is to have a turbulent flow in one side and maybe a laminar flow in another side and how that is possible it depends on many factors.

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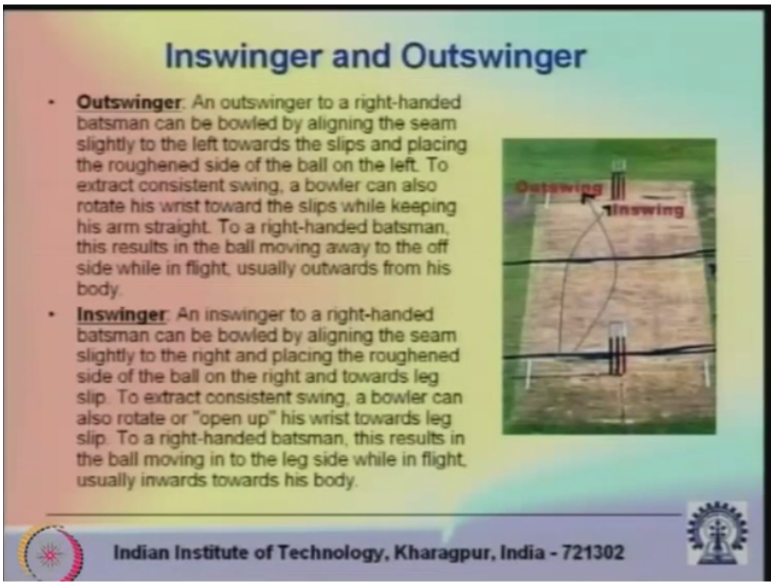

We will come into those factors one by one but just let us first for the sake of clarity try to understand that we would be first talking about a conventional swing in terms of outswingers and inswingers. So typically the outswingers as you know are the swings where the ball deviates away from the batsman and inswinger is it goes towards the batsman.

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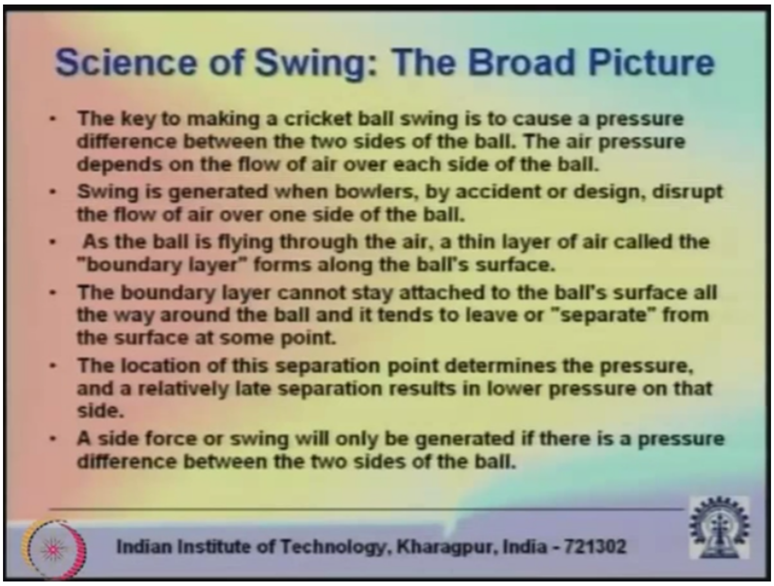

So we will try to see that how these swing balls are going to be affected in terms of a scientific perspective, so the science of swing the broad picture. So as we have discussed earlier that the key to have a cricket ball swing is to cause a pressure difference between the 2 sides of the ball. It is not just true for a cricket ball; it is true for any other ball that we may look for.

And this pressure distribution depends on the sort of local velocity of flow of air on each side of the ball. So the swing of course maybe some times generated by which sometimes by accident also and we will see that like accidentally even if you are not gripping the ball for swing how it may swing and we will see that but to have an important effect what we can say is the boundary layer sort of it may separate differently on the 2 sides of the ball.

And that is what is the key thing. So the boundary layer separation dictates the pressure distribution. The boundary layer separation may occur differently on the 2 sides of the ball and the location of this point of separation determines the pressure distribution on the 2 sides of the ball and because of the net differential in pressure the side force is generated on the ball because the ball moves from one side to the other.

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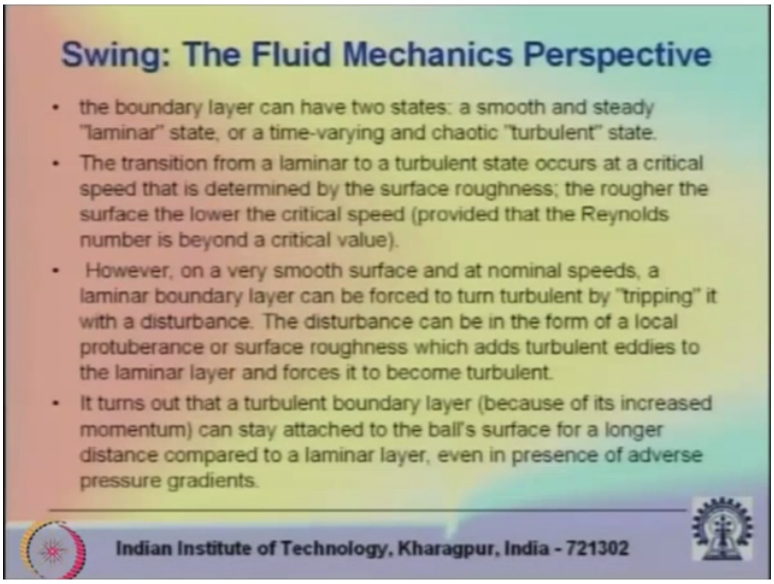

So now the question is that like as we first were discussing that what should be the effect of the speed of the ball say the speed of the ball is 145 kilometer per hour and say it is a new ball, it is equally turbulent in all sides, so the resultant side force is 0 so to say. That means if you have a very fast bowler and is holding a straight sort of seam or maybe is not holding a straight seam but with an inclined seam.

But is bowling in such a way that the flow is equally turbulent in all sides, it will not have any swing. So it is not necessary that very fast bowlers will be able to generate a swing. So what is the key for generating a swing that I mean it maybe a fast bowler but the thing is that you have to have your speed in such a way that one side of the ball the flow will remain laminar and how that maybe possible let me show that to you with a one example of a cricket ball.

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So if you look into this as an example so let us say that the bowler is bowling from the side in which I am standing so let us say that the bowler is trying to bowl an outswinger. So the outswinger the typical grip is like this. So assume that I am releasing the ball from this direction towards you so the seam will be inclined or oriented towards the direction in which the ball is expected to swing.

So typically in the direction of the slips for a right-handed batsman. So now you grip the ball in this way so this is the typical way in which you grip the ball for your outswinger. Now consider that you have the ball moving in the forward direction. So if you look into it in the other way just think that the ball is stationary and the air is coming from the other side because the aerodynamics is what which is governing the behavior.

So when the air is coming from the other side, see this seam is acting like a (()) (47:22) or the disturber on the flow. So when the air is coming towards the ball when this seam is present, so the seam will disturb the flow and if it is close to the critical Reynolds number because of this effect of the seam the ball will have a transition towards turbulence.

On the other hand, on the other side see because you are oriented the seam in the other way on the other side when the air is first coming it is not encountering the seam. So it is just falling on the surface of the ball where the seam is not present. So that means if it is a bit less or it is close to the critical Reynolds number because of a very smooth surface the disturbance will be very less, so it will tend to be laminar.

So that means the seam here is a sort of actuator of the turbulence in the flow. So because of this one you may have a net resultant force because now on this side of the ball you have a turbulent boundary layer on the other side you have a laminar boundary layer, this we are talking about a brand new cricket ball if an opening bowler is bowling with this type of a ball. So then because of the resultant force on my left side, this ball after pitching it will move in the air in that direction, so that is the outswinger.

Now if you want to bowl an inswinger, it is just the different, difference is just in terms of the grip because the same policy holds. So wherever is the seam and the ball is coming towards the seam, there it will try to have the seam will create a disturbance and have a transition towards turbulence. So if you want to swing the ball in the other way you have to just grip of the ball remains the same but the seam is now pointed towards the other end.

So when the ball comes like this it faces now first the seam in the right side where it becomes a sort of the turbulent flow on the other side it still remains laminar. Important thing is that you have to bowl it close to the critical speed. So if you bowl at a very high speed you cannot get this effect because both sides it will become turbulent and if you have very good cricketing captains sometimes they make use of these things in a very nice way.

One of the very classical examples that I can remember is like it was 5 or 6 years back, maybe 2001 or 2002, so it was Australia and South Africa test match and in that match what was happening is like I mean Australia started bowling and they opened with Glenn McGrath and Brett Lee and what was happening is that Brett Lee was bowling from a direction in which the wind was blowing.

And he was not getting any swing, the reason is he was much faster than Glenn McGrath and the air speed was helping the ball so that it was always beyond the critical speed so that it is turbulent in all the directions and despite using the new ball it was generating some pace but no movement and he is only base bowler, base batsman will always be disturbed more by movement and just by raw pace.

On the other hand, for Glenn McGrath he was bowling against the wind, so his natural speed is not that high and therefore he was not able to disturb the batsman with a threshold speed and when Steve Waugh realized it, he quickly switched the ends of the 2 bowlers and it was done in just 2, 3 overs, very quickly he did it and then Brett Lee was bowling against the wind.

So when Brett Lee was bowling against the wind what was happening is he no matter with whatever speed he was releasing the ball because of the air resistance, it came down lower than the critical speed in one side and then like it was possible to have laminar flow in one side and the turbulent flow in the other side and because of that sometimes he was getting a late movement of a late swing.

Because it depends on the relative velocity between the ball and the air and that was being modulated by the air which was blowing by itself. So sometimes if one is bowling too fast then it is not so good for a swing.

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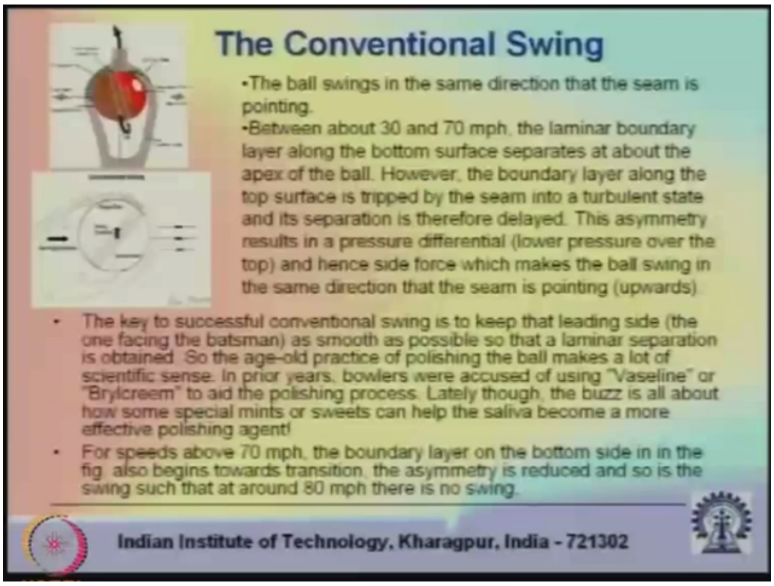

But this we are talking about a new ball and for the new ball which is being used for a swing it is important to see that it is not just a new ball that one utilizes for a swing, it is also important to have a swing even with older ball and we will therefore talk about 2 different or maybe 3 different types of swings with the older ball. So when you have older ball the thing is that you are not solely relying on the seam.

Because with the older ball if you have one side rough, the roughness of the ball may itself trigger turbulence. So then you are not depending on the effect of the seam alone of course you grip in the ball in the same way but no matter whatever is your grip I mean say you are griping it in a traditional way for a particular swing say outswing but now this side of the ball say is roughened.

So the contrast between the roughness between the 2 sides of the ball is if it is very, very strong because of the high smoothness in one side it may be ensured in many ways. We have seen many illegal ways in which many of the teams have tried to do it. So the key is in one side you keep it very smooth, another side you keep it very rough and then the rough side will have an automatic triggering to turbulence and using that even with the older ball, you may be able to swing.

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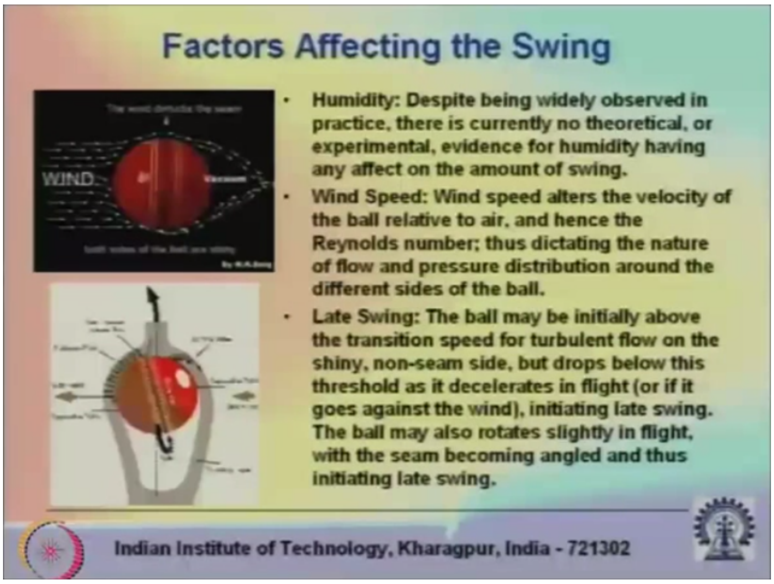

And of course again it will matter that what is the relative speed between the ball and the air. Now there are many factors which might affect the swing, one of the important factors people believe is the humidity and we have always heard that in a highly humid condition, the ball is expected to swing much more but there has been no evidence of that from a fluid mechanics perspective.

Because the density change or viscosity change with the relative humidity change is so small that the Reynolds number change is not sufficient and from the fluid mechanics perspective Reynolds number should have been the dictating factor. So perhaps something else happens in that situation and still it is an unresolved question in fluid mechanics.

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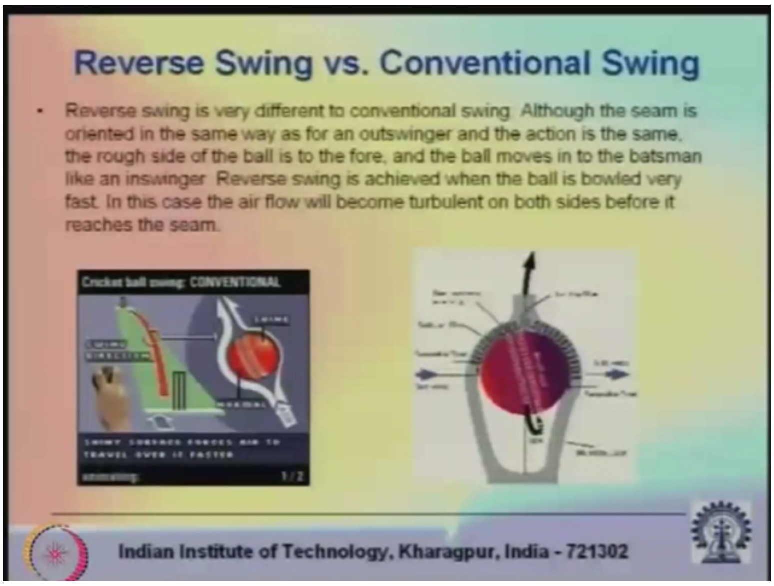

Now if you consider something called as a reverse swing. So the reverse swing the whole idea is that the ball will now swing in the direction not in the traditional way but in the other way and the whole idea is that if you now see that you grip the ball in the same way say as an outswinger like this but now you make this side of the ball rough, so you grip the ball like a outswing delivery.

But you make this side rough and the other side smooth just the opposite to the normal swing case and then what will happen is if you consider the flow that is there on the ball then you will have so in the side where you are making it rough, it will become turbulent, on the side in which you have kept it smooth because of the effect of the seam it will become turbulent but the triggering of turbulence is different in the 2 sides.

So the flow will not separate in the same symmetric position in the 2 sides. So in 2 sides the flow will be turbulent but there will be a difference in the point of separation and that will generate a net sidewise force which is just opposite to the way you are showing it by your grip. So good batsman will know by looking into the side which side is rough and which side is polished that like what should be the nature of the swing.

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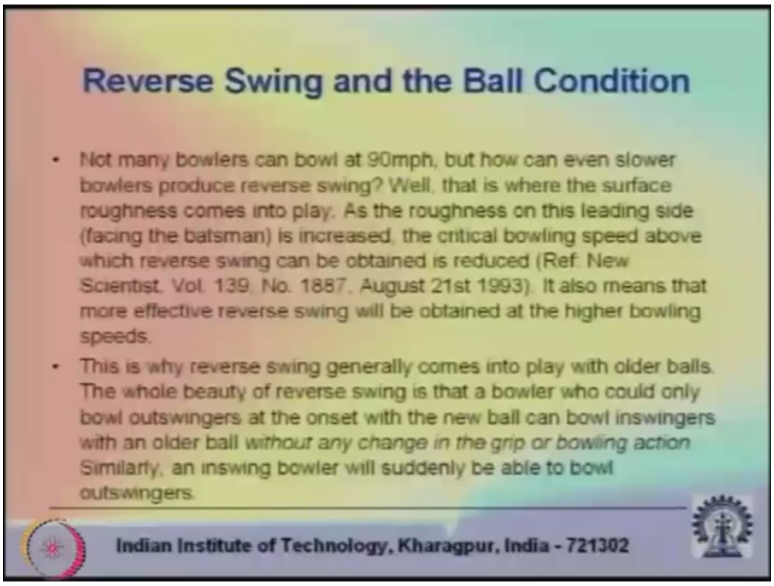

Now of course the reverse swing one of the things is that it is also a strong function of the condition of the ball and therefore like issues of tempering of the ball and roughening of the ball using illegal means have come into the play.

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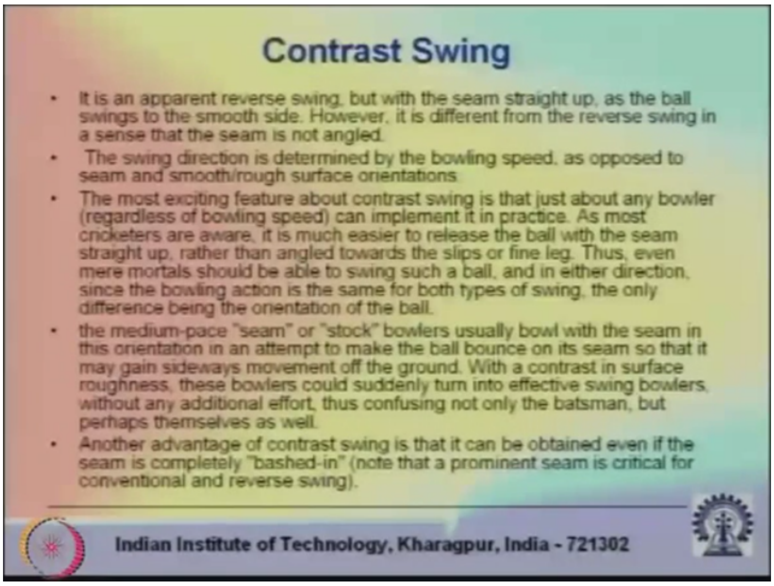

A third type of swing which has not come into the picture till very recently is known as contrast swing. So contrast swing is such a swing which is not so much dependent on the seam of the ball, so unlike the traditional swings where the seam is held in a inclined direction I mean where you want to move it. In the contrast swing, the ball is held with the seam straight.

So the seam is held perfectly straight and for a novice bowler it is much easier to hold a seam straight rather than holding it in an appropriate direction for the swing.

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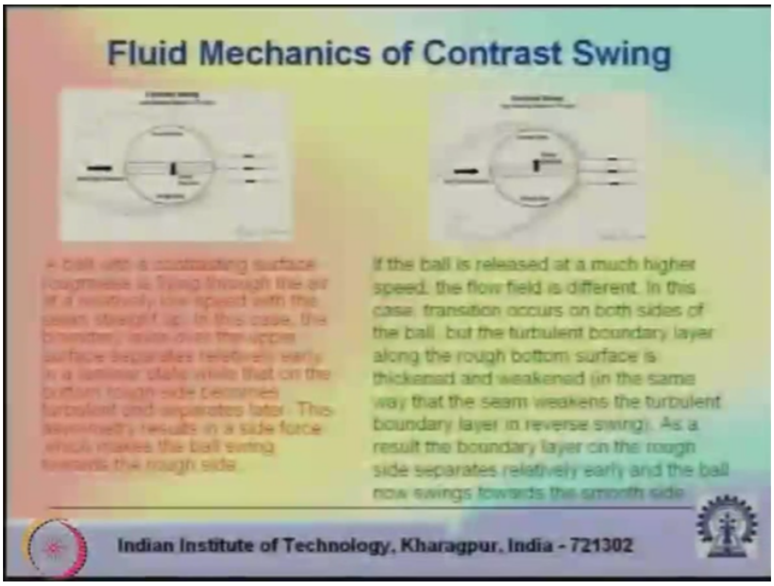

So what happens in a contrast swing, if you see that just look into this visual where you have in the left side a ball with a contrasting surface roughness flying through the air and the seam is straight up. So the name contrast comes from the contrasting roughness on the 2 sides of the ball. So in this case the boundary layer over the upper surface separates relatively early in the laminar state.

Because the upper surface is smooth whereas on the bottom surface it separates later this asymmetry results in a side force and it moves in the direction which is facing in the other way. On the other hand, if you just reverse the roughness and the smoothness you may make it move in this way and since the effect of the seam is not there even in a torn out or a ball which has got a lot of wear and tear and the seam is not very prominent you can have this type of swing.

And this is known as contrast swing but like before closing our discussion let us just look into some of the very good swing bowling's, great bowlers who perhaps never knew what is the fluid mechanics of swing.

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But could produce the swing in a much better manner than anybody else in that would perhaps do.

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So let us look into this like Sarfraz Nawaz was considered to be the inventor of reverse swing. So we will just slowly see some of the examples like you can see before this we saw Imran Khan, then Wasim Akram and like these were great exponents Waqar Younis, these were obviously great exponents of reverse swing bowling.

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And like this is a typical inswing yorker and you can see that what were the conditions of the batsman during that time. Aqib Javed was also one of the very good bowlers and of course you can see Shoaib Akhtar one of the devastating bowlers of the modern times.

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Now just finally we will see one clip like it was 2005 Ashes series which was known for the series where you had reverse swing, contrast swing and all these things. So you can see this like one of the balls delivered by Flintoff and another ball in the same clip delivered by Simon Jones and these balls will illustrate that how these types of swings are there. So the second ball will illustrate in a bit more interesting way so just look into it.

So like these are typical cases of reverse swing bowling and perhaps this is the first time that English men could find out that how to bowl good reverse swings and it was good enough for them.

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So look at the deviation in the ball and it was the ball was gripped entirely in the opposite direction, it was gripped as if it was going to move in other direction. So maybe we just stop here today in this lecture and from the next class we will continue with the new chapter that is pipe flow.