Engineering Mechanics
Prof. K. Ramesh
Department of Applied Mechanics
Indian Institute of Technology, Madras

Module – 02
Dynamics
Lecture – 11
Rotating Frame of Reference V – Understanding Coriolis Acceleration

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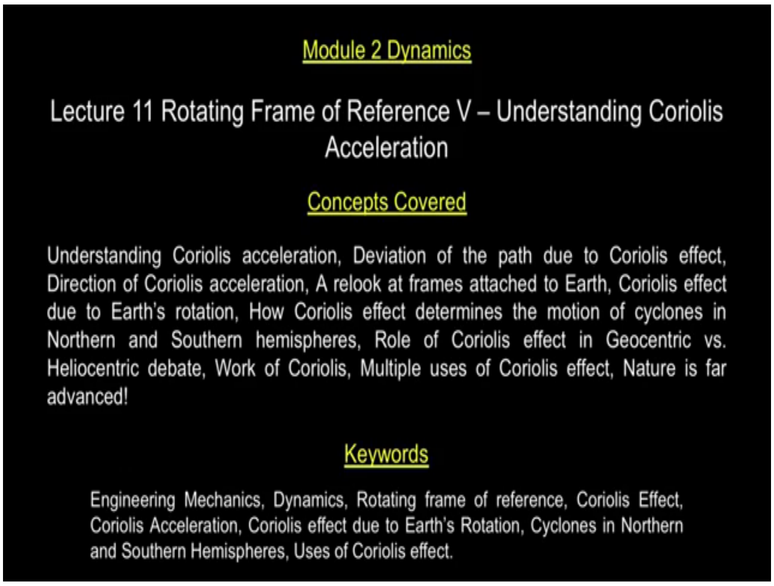

So, let us continue our discussion on rotating frame of reference and we will try to understand Coriolis acceleration better in this lecture.

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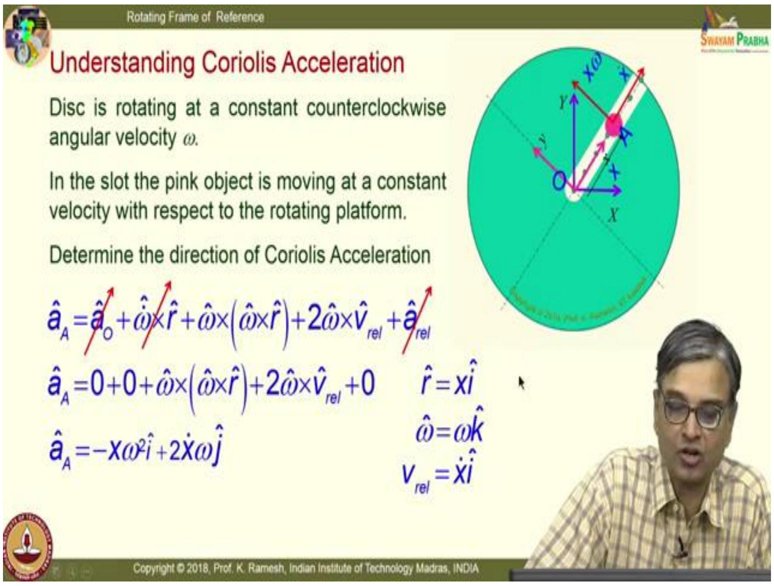
So, I have taken the very famous example of a straight slot on a rotating platform and it is rotating in a counterclockwise direction. And you have a particle pink in colour is moving in the slot. And what we are going to do is, we are going to understand it from first principle so that we make the problem very simple, knock off several terms and just focus on the Coriolis acceleration.



So, what I have here is, I have a velocity in the direction of the slot. And I have the position marked as X and this is like your *r*. So, *rω* is the velocity because the platform is rotating. And you have $\dot{x}$ is the velocity the particle is moving in the slot. See, I am going to repeat this animation several times. In each slide you will first see this animation.

The idea is to get the idea of what is happening to the particle as clearly as possible. And I have labelled the particle as A and I also label the centre of the disk as *O*. And you have this fixed frame of reference like this. And the rotating frame of reference is aligned to the slot at this moment. It is rotating with the platform. And you know very well that the acceleration of the particle *A* is nothing, but $\hat{a}_A = \cancel{\hat{a}_O} + \cancel{\hat{\dot{\omega}}} \times \hat{r} + \hat{\omega} \times \left(\hat{\omega} \times \hat{r}\right) + 2\hat{\omega} \times \hat{v}_{rel} + \cancel{\hat{a}_{rel}}$.

We have already said that disk is rotating at a constant counterclockwise angular velocity *ω*. So, which implies that *ω* dot is 0. I will deliberately make many terms 0 fine to make our life simple. And I have *O* is a fixed point and we have also said that in this slot the pink object is moving at a constant velocity. So, all these terms are very important to interpret. So, when I say the velocity is constant, I would also have this term knocked off.

So, I have $\cancel{\hat{\dot{\omega}}} \times \hat{r}$ is knocked off. I have a constant velocity of the particle in the slot. So, the a_{rel} is knocked off and I have $\cancel{\hat{a}_O}$ that is also knocked off because it is a fixed point. So, I am left only with the $\hat{\omega} \times \left(\hat{\omega} \times \hat{r}\right) + 2\hat{\omega} \times \hat{v}_{rel}$. And you have an expression for V_{rel} ok. You have this as $\hat{r} = x\hat{i}$. So, $v_{rel} = \dot{x}\hat{i}$. So, that is what is shown as velocity $\dot{x}$ here. So, the particle A has a velocity $\dot{x}$ in this direction and also a velocity component *xω* in this direction.

So, finally, when you simplify, the acceleration of the particle A simply reduces to $\hat{a}_A = -x\omega^2\hat{i} + 2\dot{x}\omega\hat{j}$. And we have $\hat{\omega} = \omega\hat{k}$ and $\hat{r} = x\hat{i}$, all these quantities are very clearly labeled.

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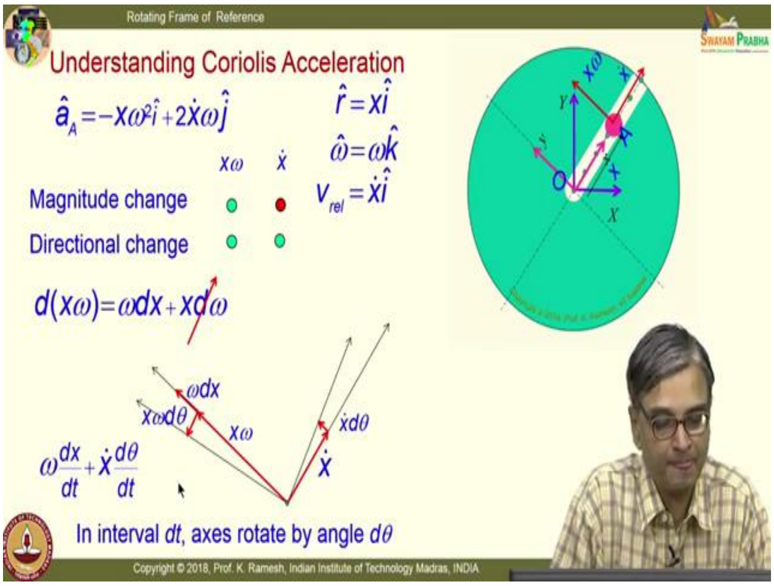
And again, I will have the particle is rotating. So, you get an idea of this. And what we are going to look at is, I have labeled them as *A* and *O*. I have this and I also have the expression for acceleration. I will understand the terminologies.

So, I put the axis here at this instant of time. And what are the velocity components I have? I have a velocity component $\dot{x}$ in the direction of the slot. And I also have another component of velocity which is $X\omega$. I have deliberately shown that they are not equal. I could not show it in this diagram this too small for me to show. So, when I do it here just to bring in a generality that these 2 quantities can be of different magnitude to start with. Now what we have to do is, we have to investigate for a small rotation $d\theta$, what happens to these quantities. And what is it a person would perceive sitting on a rotating frame, what is it that he will not perceive sitting on a rotating frame? And when I say the changes in velocity, we have always looked at change in magnitude and change in direction both contribute to the acceleration ok.



So, in an interval dt, axes rotate by angle $d\theta$. So, let me draw that and I would appreciate that you make a neat sketch of it. And I will also repeat this sketch once more so that, if you miss out some of the details you could fill them up in the second time. So, I have this rotated by $d\theta$. Now, what I would like to investigate is, from the problem statement how these quantities change that, you have to look at. So, I have to look at the magnitude change as well as the directional change.

So, let me summarize. I have 2 components of velocity. One component of velocity is $X\omega$, another component of velocity is $\dot{x}$. What is given in the problem statement? The particle moves with a constant velocity fine, $\dot{x}$ remains constant. So, there is no magnitude change of $\dot{x}$. On the other hand, when I have this *Xω*, *Xω* does have a magnitude change.

So, how would I write this? I have *Xω* so I differentiate it. So, when I differentiate it, I get this as $d(x\omega)=\omega dx+x\cancel{d\omega}$. And it is also given in the problem about what way *ω* is changing. It is clearly stated to make our life simple that the disk is rotating at a constant angular velocity. What is the meaning of that? I cannot have *dω*. So, *dω* goes to 0.

So, what I have here is, the component of velocity *Xω* has a magnitudinal change of the value *ωdx*. So, I have this *ωdx*, is the magnitudinal change. And I have already discussed what happens to the magnitude change of $\dot{x}$. It is given clearly in the problem statement; $\dot{x}$ remains constant. So, I have this magnitude change is 0. Now, let us look at the directional change.

The directional change exists for *xω* and that is depicted like this, *xω dθ*. And I also have a directional change of $\dot{x}$, that is depicted as $\dot{x}$ *dθ*. See, what you will have to look at is a person sitting in the rotating platform because he is rotating with the platform; he fails to recognize these two quantities. You know, this was the most difficult aspect when people were making the measurement and comprehending without the assistance of mathematics. But, with the assistance of mathematics there is no difficulty at all. You get all these terms one after the other. You have to be very consistent in your mathematical development.

So, when you differentiate it with respect to the time, I have this as $\dot{\theta}\ \dot{x}$ and $\dot{x}\ \dot{\theta}$that is what you got it here ok. I have this as $\dot{x}\omega$.. I can refer I can refer this as $\dot{x}\omega$.. This is what you are not able to see when you are sitting on the rotating frame of reference that has contributed to the Coriolis acceleration fine.

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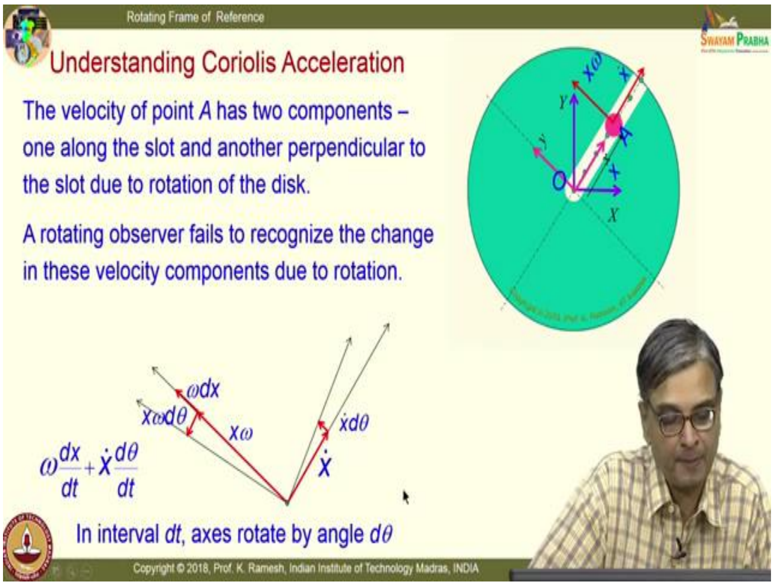
So, the velocity of point has two components, one along the slot and another perpendicular to the slot due to rotation of the disk. A rotating observer fails to recognize the change in these velocity components due to rotation, which is what I had explained. I said that I am going to redraw this again so that you can fill up any missing links in your notes.



So, I have $\dot{x}$ and $x\omega$. And I rotate it by an angle $\Delta d\theta$. So, I have explained how I have got this omega d x and I have also explained how I have got this $x\omega d\theta$ and I have also explained how you have got $\dot{x}d\theta$. So, the rotating observer fails to recognize $\dot{x}d\theta$ and ωd x.

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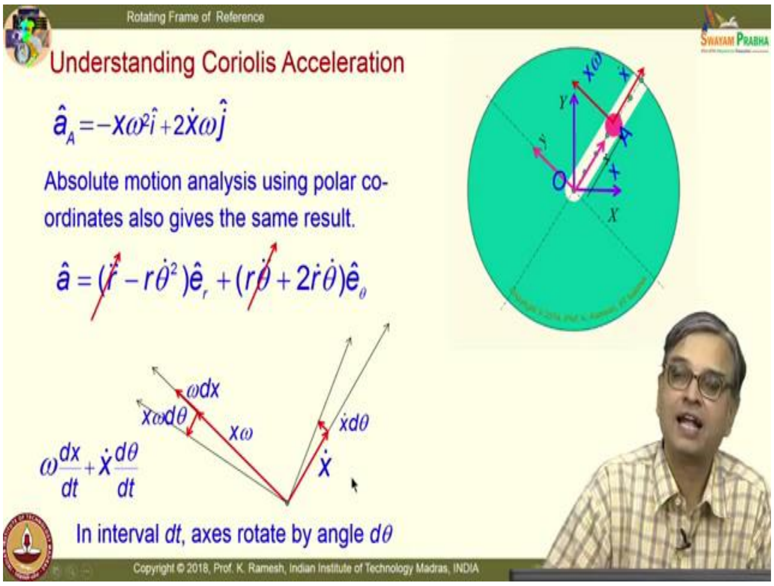
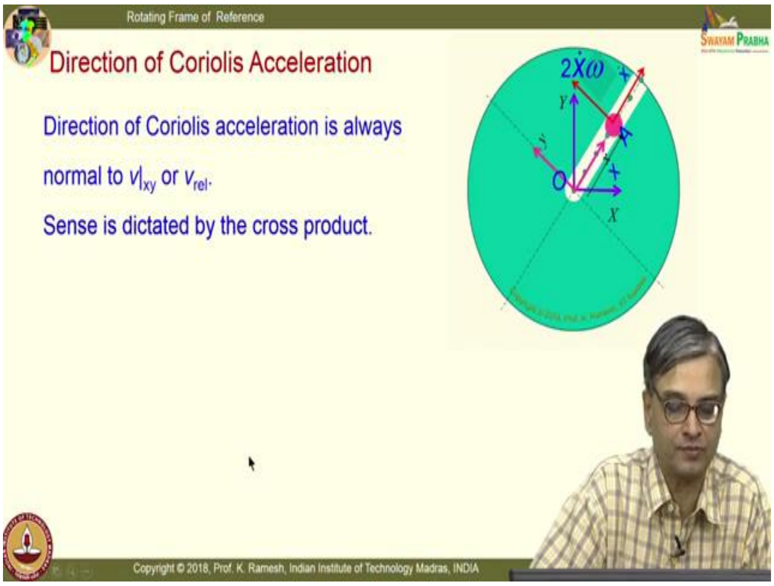


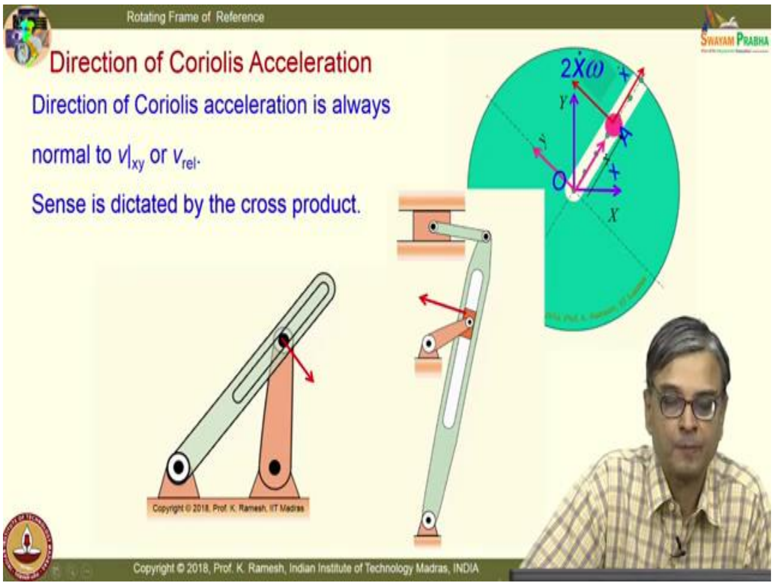
I have this as the basic expression. And if I do absolute motion analysis using polar coordinates, also gives the same result. There is no difference at all. Let us go back and get that expression. I have this as $\ddot{r}-r\dot{\theta}^2$. In fact, after a long discussion of the problem which we discussed in the previous class, this is very easy for you to comprehend.

See, the idea of repetition is to firm up the concepts that you have learnt. That is the idea behind it ok. And the healthy repetition is desirable in learning the course. From the problem statement, r double dot is 0. From the problem statement, theta double dot is also 0. So, here again, I get very similar expressions ok you should recognize these identities.

If you are in a position to solve the problem using polar coordinates, no harm in it fine.



But, when you learn the rotating frame concept, it helps you to expand your scope of solving problem. Particularly, when you are dealing with rigid body mechanics, you should apply it. And you can physically appreciate the solution procedure. And this is again repeated for clarity.



So, whether I do with the rotating frame of reference or do an absolute motion analysis, there is absolutely no change as far as the acceleration of the particle.

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And what is the direction of Coriolis acceleration? We will also summarize for the earlier problems as well. So, we have this noted down and direction of Coriolis acceleration is always normal to the V_{rel} or $V|_{xy}$ sense is dictated by the cross product. Normal is fine, but sense is dictated by the cross product. So, in this problem I have this as $2\dot{X}\omega$ perpendicular to the slot. You should recognize that this is perpendicular to the slot a similar story you will find in other problems also.

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See, we have solved the quick return mechanism and also the, a slotted member and another member like this. So, I have this as $2\dot{x}\omega$ for this. And then in this problem also we have looked at. And this particle is coming down. So, when you look at the cross product, the Coriolis acceleration is perpendicular to the slot. And in the quick return mechanism, we have also looked at this and this is perpendicular to the slot like this.

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Where does this affect us? It is a very interesting application.

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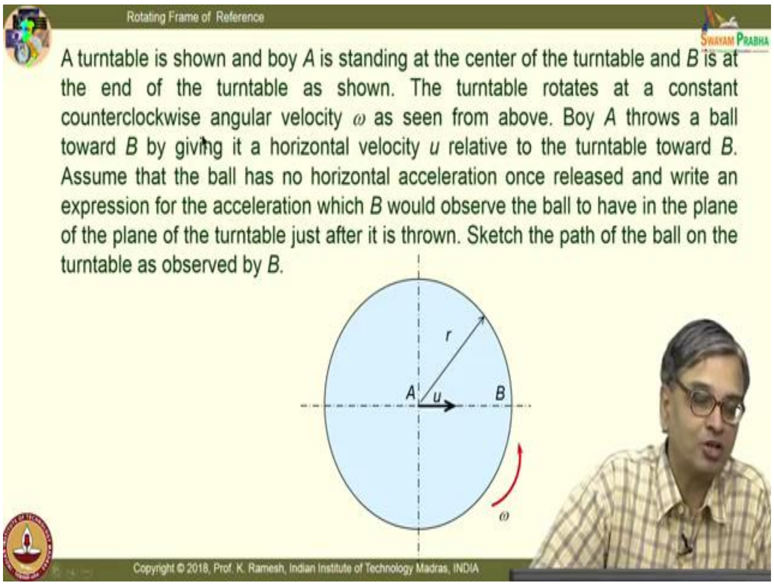
And you look at here. The hand is stretched, because of the Coriolis force the it is drifting away.

And look at the switches here. This is in a space station they are provided with a protection like this. And I will repeat the animation once more ok. So, you have a spinning space station. And if I have to operate the controls, I must go and operate the correct switch. Look at look at the hand. Look at the hand, their hand is going there. Because of this protection he is able to, he or she is able to remove the hand from this and go to the switch and switch on this. It is a very interesting one. This is published by NASA.

So, it is a very practical application of direct feeling of where the Coriolis force influences you because we have come out of a space age. The prediction is, another 20 years people can go to space and come back as tourists fine. So, you for all this spinning, they have to be spinning for stability. And look at here we have seen that perpendicular so that hand is free. So, hand is drifting without your control. Your intention is to keep the hand straight. Because of the rotation, the hand is pushed away ok. So, it is a very nice illustration and we will also look at very interesting problem ok.



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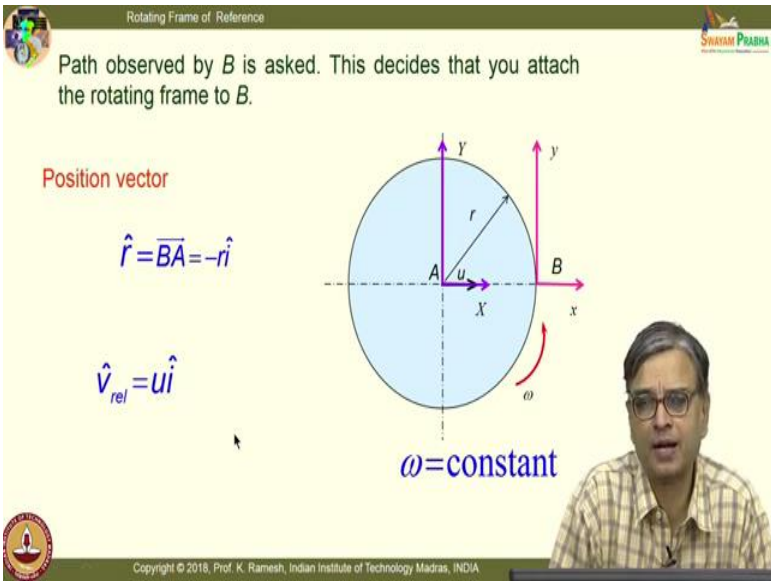
We go back to the turntable. Please write down the problem statement. And interpret the problem statement properly. Because, you need to understand that we are sitting on earth and observing things. For all practical purposes, we have considered earth is a stationary fine, but it is the rotating frame of reference.

So, it is a very nice problem which tells you, from a rotating frame of reference, what is it that you observe. And it is a very simple problem which you can easily handle it. Boy A is standing at the centre of the turntable and B is at the end of the turntable. I have 2 boys standing. The turntable rotates at a constant counterclockwise angular velocity omega as seen from above. We have already seen that it is rotating. I have animated that and it is a constant angular velocity.

So, omega dot is 0. Boy A throws a ball toward *B* by giving at a horizontal velocity u relative to the turntable towards *B*. See, the boy is standing and throwing the ball. But the ball is in space, it is not constrained by the slot like what we have seen in the previous problem. And for a rotating observer, he will observe a constant velocity *u*. That is what the problem statement says, to make our life simple ok.

Assume that the ball has no horizontal accelerations once released. And write an expression for the acceleration which *B* would observe the ball to have in the plane of the turntable just after it is thrown. So, the pulse of this problem is, sitting from a rotating frame of reference, what would you observe? That is the idea behind this problem. So, I am going to put the rotating frame of reference where? I will attach it to the point B because when I put the rotating frame of reference, I have already said the observer sitting at the origin and observing what is happening. When a ball is thrown in space, there is no connection between that and this. What way it will travel in space? It will still have a straight path.

But you know very well because the turntable is rotating, it is not going to reach the person. The person will not be able to catch it, but the person will apparently see that the ball is deviating. It is only a perception from the rotating frame of reference. And what we are going to later relate is, you are sitting in a rotating frame of reference your observing cosmological things. That is what we are going to relate it to fine.



All along we have solved problems neglecting that in certain class of problems you cannot neglect it. And you can understand it only when you feel that you are sitting on a rotating frame of reference and do it. So, from that perspective this is a very interesting problem. So, it is going to help us to understand cosmological happenings that you observe from earth which is the rotating frame of reference, which we have neglected it all along.

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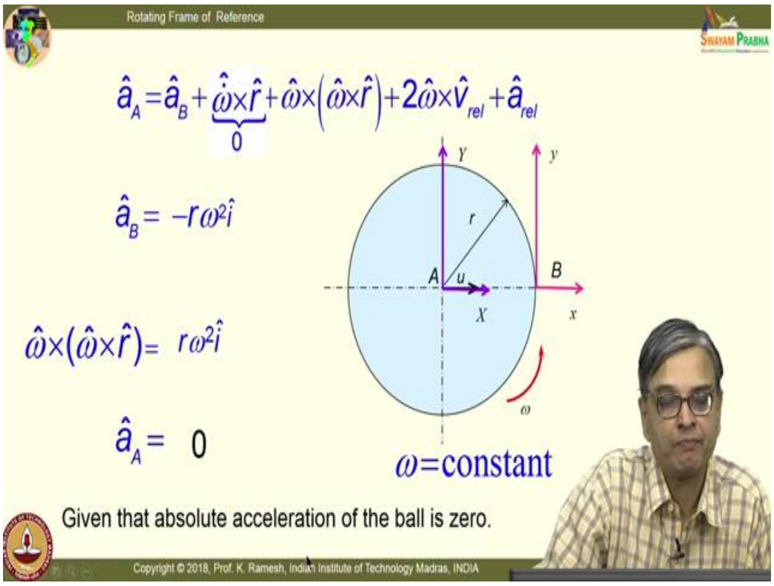
So, path observed by B is asked though this decides that you attach the rotating frame to B. Is the idea clear? See, I have taken pains to explain you in various different ways how to identify a fixed frame of reference and how to identify a rotating frame of reference. The moment you identify this, rest of it is simple algebra which you are master at it. The thinking part is only on the selection of the fixed frame of reference and rotating frame of reference. You should not rush up at that stage of solving the problem. So, I have the rotating frame attached to the point B. And you have a fixed frame attached to the centre. And it is given in the problem statement to make your life simple.



A rotating, a person sitting in the rotating platform would observe a constant velocity u. And we will also have to get the position vector, $\hat{r} = \overrightarrow{BA} = -r\hat{i}$. I am taking the rotating frame of reference as the basis for all my calculations. So, it is $-r\hat{i}$ and I have $\hat{v}_{rel} = u\hat{i}$ given in the problem statement, very clearly given in the problem statement. Here, observer sitting in the rotating platform would observe a constant velocity *u*.

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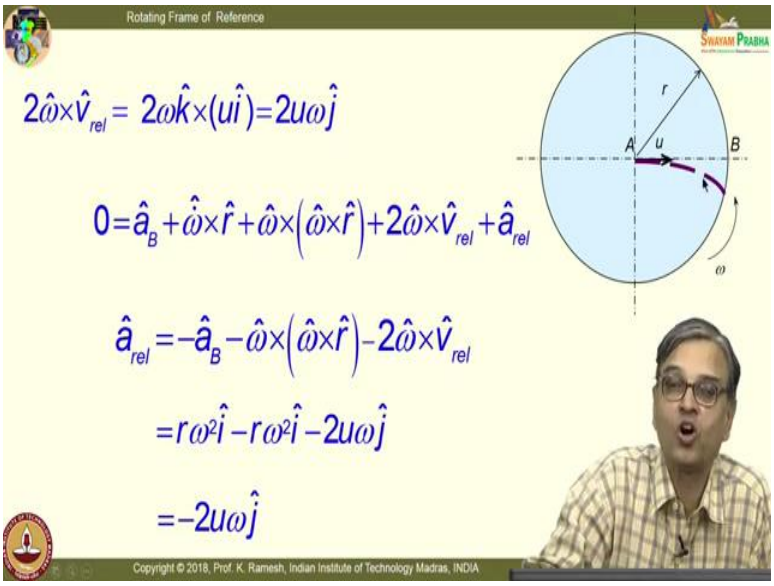
And I have the standard expression for acceleration of point *A* because he is going to observe the ball thrown at *A* thrown by the boy at *A*. And it is also given the problem statement, what is it that you have given as acceleration of *A*. Go back to the problem statement and then see. It said that you assume there is no horizontal acceleration fine.

You are just having a constant velocity; the ball is moving at a constant velocity. And if you look from space, it will go in a straight path. If I sit on the rotating platform, I will not see that it is going in a straight line.

So, what all things I know? I have this as a rotating platform just to show that this rotating frame of reference rotates like this ok, rotates like this. And I can find out what is the coordinate acceleration for me to fill up all this. We have already noted some other terms are 0. And you can easily write $\hat{a}_B = -r\omega^2\hat{i}$ because this is rotating, very simple and straightforward for you. And I have this $\dot{\hat{\omega}}\times\hat{r}$ is 0 because $\dot{\hat{\omega}}$ is 0. And we also have omega cross omega cross r that is r omega squared i. And we also have in the problem statement that there is no acceleration in the horizontal direction. So, $\hat{a}_A = 0$.



So, we have to get what is the acceleration that the observer B would observe for the ball. And you know, you will also have to go back if I have to sketch the motion of the ball. You have to go back to your projectile motion. You have also looked at a projectile is just thrown and what is the shape it takes place, u it is moving in a constant gravitational field. It has a parabolic motion, is not it? In the vertical plane it has a parabolic motion.

Here, we are discussing about the horizontal plane fine. We are looking what is happening, the vertical plane is, is bound to happen. In addition to that, in the horizontal plane what happens? Because the platform is rotating, rotating anticlockwise. I have given you the clue for you to visualize what should be the nature of deflection.

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So, when I do this $2\hat{\omega}\times\hat{v}_{rel} = 2\omega\hat{k}\times(u\hat{i}) = 2u\omega\hat{j}$. And I have this, 0 equal to the rest of the expression is written, it again the 0 quantities are not fully removed. So, I essentially have this. I have $\hat{a}_{rel} = -\hat{a}_B - \hat{\omega}\times\left(\hat{\omega}\times\hat{r}\right) - 2\hat{\omega}\times\hat{v}_{rel}$. So, the quantity what an observer sitting on a rotating platform would observe as acceleration and we will soon relate it, people sitting on earth, it is a rotating frame of reference, not a fixed frame of reference.

We have all along discussed, when I say a_{rel} or V_{rel}, I said, what the quantity that you measure from the rotating frame of reference XYZ, small xyz ok. So, that is what expression you have. And you already have what is a B and this quality. They cancel each other. So, I essentially get this as $2u\omega\hat{j}$.

Now, the stage is set for you to visualize what should be the pattern of deviation of the ball. What does this indicate? See, the ball will have to traverse this radial distance fine that is what you are trying to look at. And this is now moving in a constant acceleration field, like what you had in your projectile motion you have the acceleration due to gravity. Here, I have a constant acceleration $-2u\omega$. So, what way the deviation would be? It would again be a parabola ok. So, that is what you see here. The person would observe, the person would observe, this particle experiences a motion like this in the horizontal plane. Is the idea clear? Is the idea clear?

Suppose, I look from above, I would see the ball as only a straight motion fine. For a observer who is the outside the rotating frame of reference, when he observe it, it will go only in a straight line fashion. It does not deviate. Because the person is sitting in a rotating platform and rotating with it and we are also explicitly calculating the a_{rel}, I see that this is in a constant acceleration field for the entire length. So, this deviates like a parabola ok. And this is what is affecting when you observe things from the earth.

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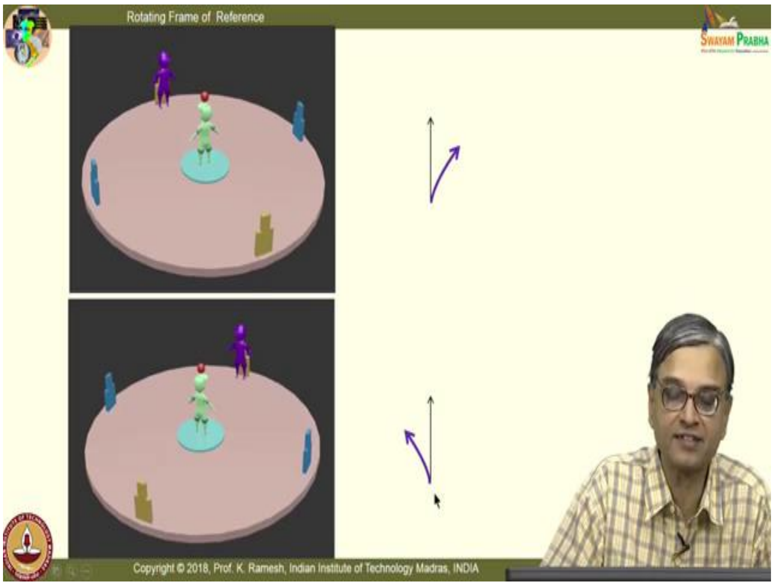
So, you have a nice 3-dimensional visualization of how the ball is deviating for the observer B in this animation. I can repeat the animation. The platform is rotating anticlockwise and the ball deviates like this. And the deviation is shown as a curve here. For an observer who looks above, the ball would only travel a straight path. The deviation is observed by the observer sitting on the rotating platform. Suppose, the rotating platform instead of rotating anticlockwise if it rotates clockwise, what happens? The deviation is to the left like this.



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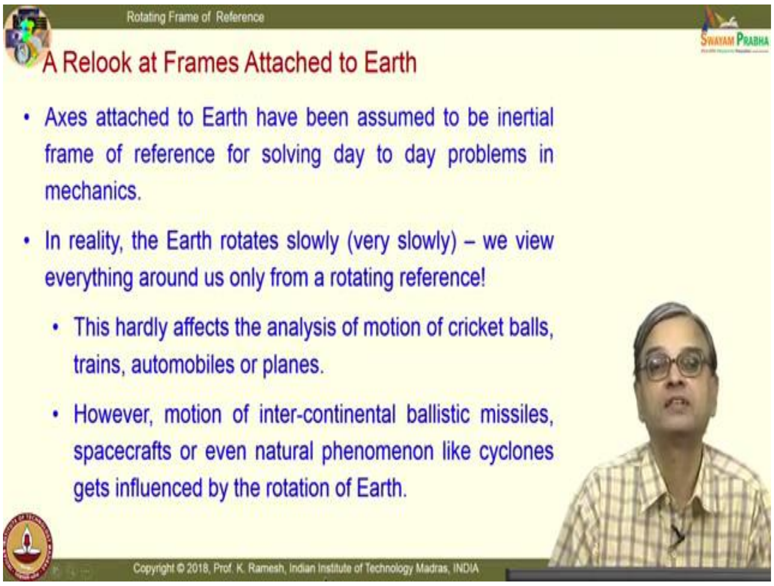
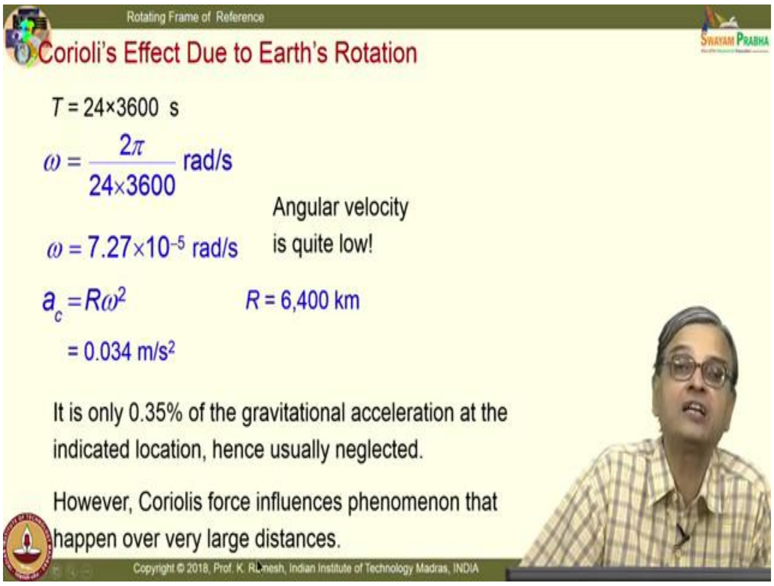
And now, let us look at a relook at frames attached to earth. Axes attached to earth have been assumed to be inertial frame of reference for solving day to day problems in mechanics.



In reality, the earth rotates slowly, very slowly. That is the reason you do not sense that. We view everything around us only from a rotating reference. Fortunately, it is not affecting the motion of cricket balls, trains, automobiles or planes. However, motion of intercontinental ballistic missiles, spacecrafts or even natural phenomenon like cyclones gets influenced by the rotation of earth. See, all along in mechanics, it was a very convenient reference point to take fixed frame of reference attached to earth.

Now, you have to realize that we are sitting in a rotating frame of reference which influences certain phenomena that, we have not been able to understand hitherto.



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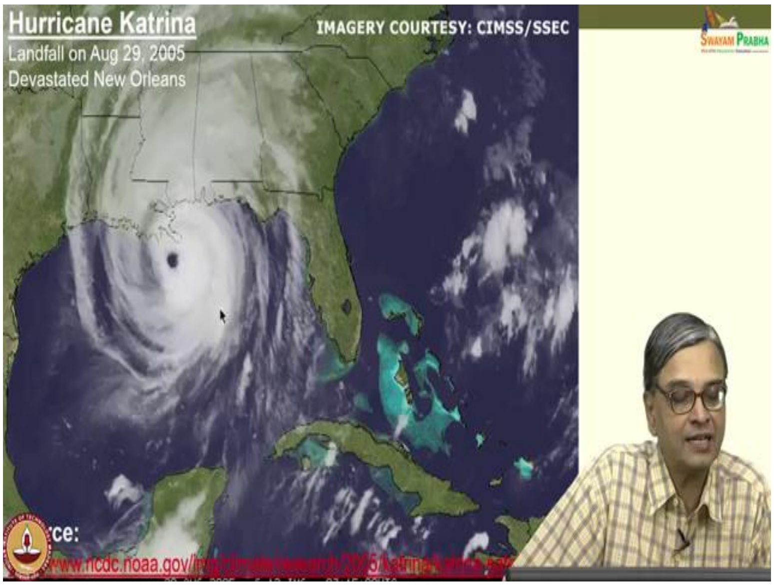
We will also calculate what is the value of earth's rotation. It is very slow. I have this as the time period, 24 hours. And if you estimate the angular velocity, this turns out to be a very small quantity of the order of 7.27×10^{-5} rad/s. It is very small. And it is also worthwhile to note, even if you calculate R omega squared when R is so high as 6400 km. The acceleration is only 0.034 m/s^2.



So, in comparison to acceleration due to gravity, it is only 0.35% hence usually neglected. However, Coriolis force influences phenomenon that happen over very large distances.

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So, you have a Hurricane Katrina. This is in the northern hemisphere. And you could observe what is the rotation of this cyclone this is in an anticlockwise rotation.

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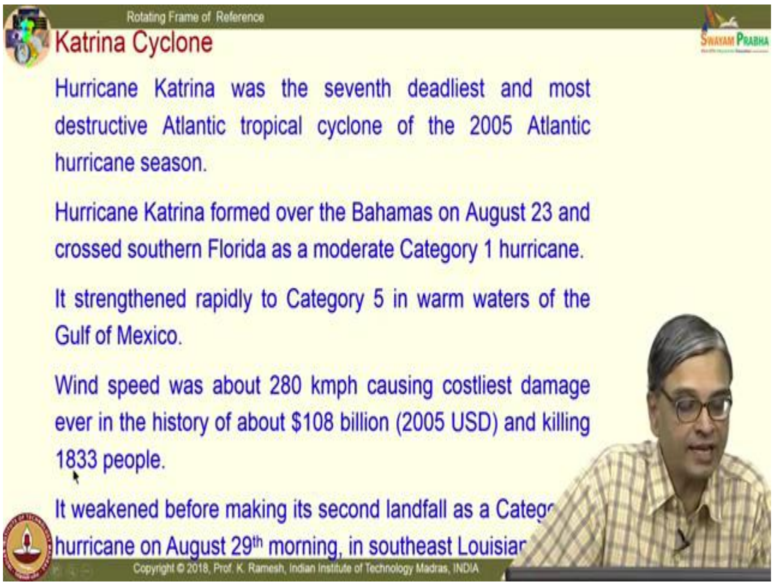
And there is also data on how severe was the cyclone Katrina. This was the seventh deadliest tropical cyclone of the year 2005.



So, it started as a category 1 hurricane. Strengthened rapidly to category 5 in warm waters of the Gulf of Mexico, wind speed was about 280 km/hr causing costliest damage ever in the history, of about 108 billion in 2005 and killing 1833 people. It weakened before making its second landfall as a category 3 hurricane on August 29th morning, in southeast Louisiana.

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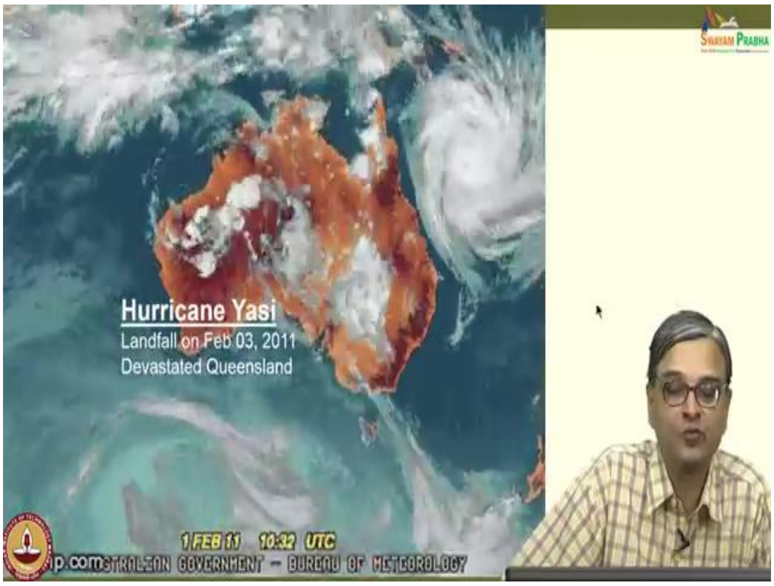

Then you also have another cyclone heading Australia. It is very striking to see that the cyclone is in clockwise direction. This is again a very important cyclone. You have this as, named as Hurricane Yasi.

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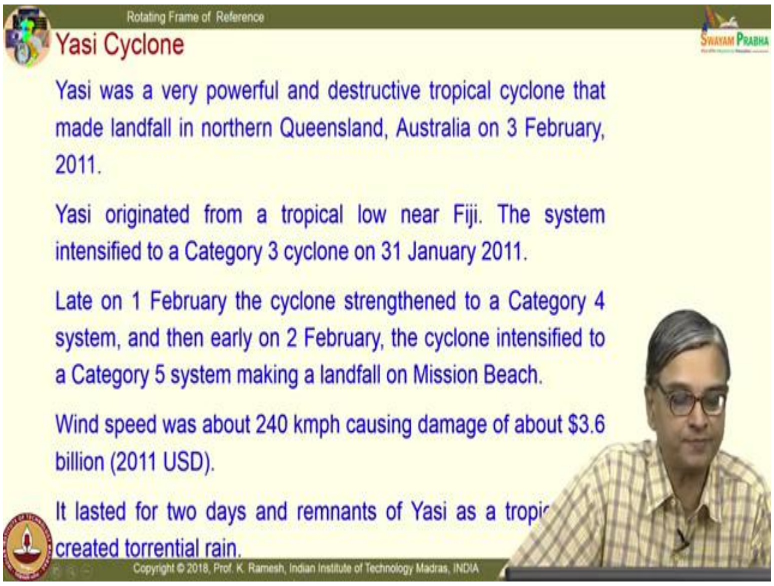
It was a very powerful and destructive tropical cyclone made a landfall in northern Queensland. intensified to category 3 on January 2011, 31st January 2011 and strengthened to category 4. Then, on 2nd February, the cyclone intensified to category 5 making a landfall on Mission Beach.

Here, again the speed was very high, of the order of 240 km/hr. Damage is estimated to be slightly less, in the order of just 3.6 billion again, a huge money. It lasted for 2 days and remnants of Yasi as a tropical low created torrential rain.



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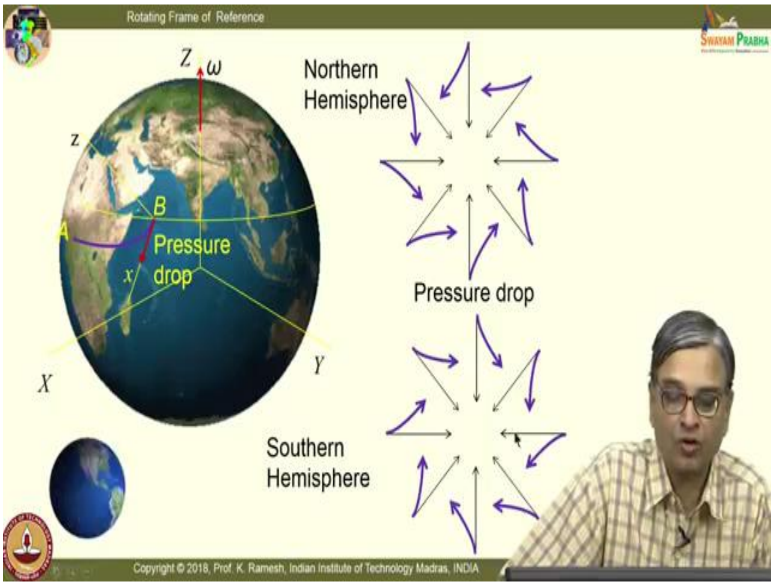
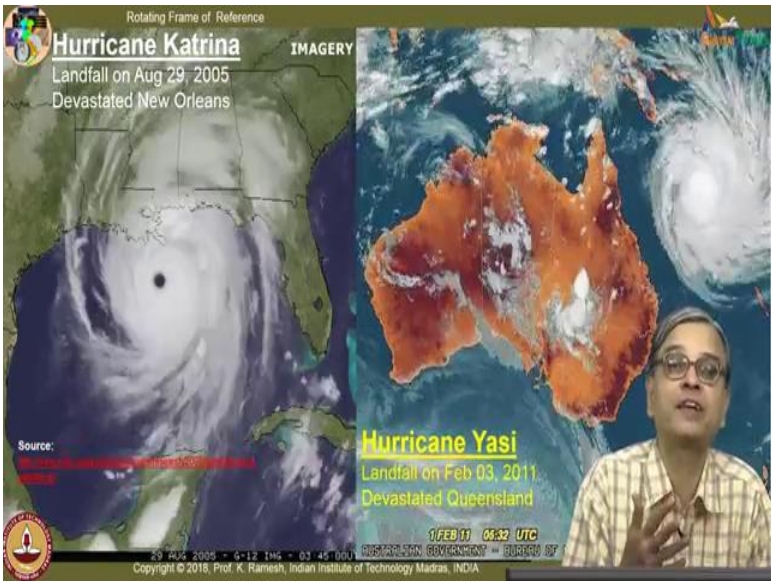
So, from the mechanics point of view, we would like to understand why the cyclones are having different rotations in different hemispheres. This is mainly because of the Coriolis Effect. So, when there is a pressure drop in the northern hemisphere because the earth is rotating like this, it is anticlockwise in the northern hemisphere. And this deviates like this. This causes the northern hemisphere cyclones to have an anticlockwise rotation.



On the other hand, when we come to the southern hemisphere, it is rotating in the clockwise direction. And the deviation of the wind is like this. This causes the cyclone to rotate in the clockwise direction.



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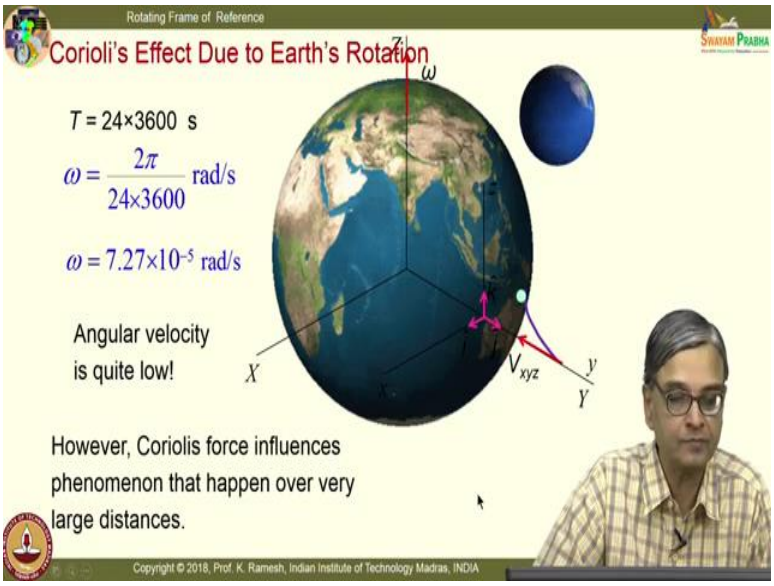
So, this provides a scientific explanation, why do the cyclones have different rotation in the northern hemispheres. People were not able to understand it earlier. Only after understanding Coriolis Effect, they were able to interpret these effects because of Coriolis action and you could also see here, again from the rotating platform. We are sitting on the rotating platform and viewing it. And you we see the deviation to the right like this, when it is anti clockwise, when it is clockwise deviation to the left. So, this translates into cyclones having anticlockwise and clockwise motion in northern and southern hemispheres.



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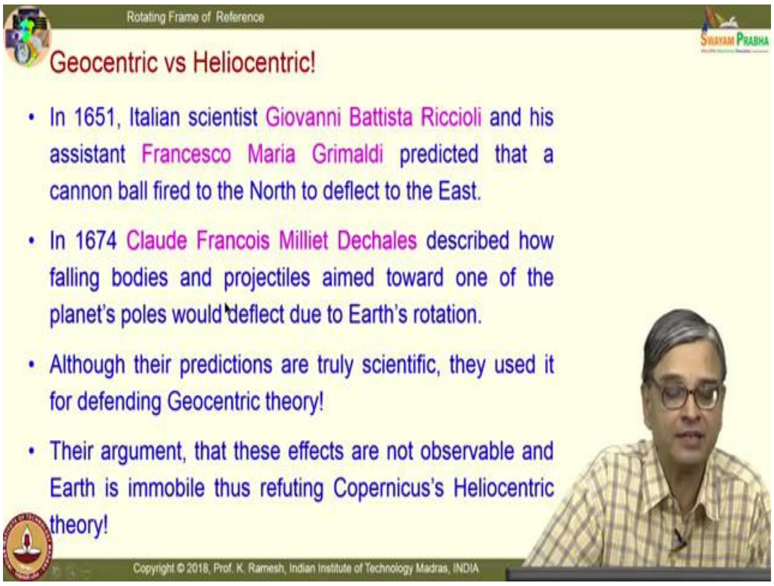
And you should also realize that when there is a ballistic missile which is heading far away, if you do not account for the Coriolis Effect, it is not going to hit. In fact, the history says in the 2nd World War, Germans were targeting Paris. And it is about 120 kilometers away from their place they were not able to hit the city of Paris. It was deviating because of Coriolis

Effect thankfully. And here, it says that whenever there is a falling of the object, if you do not take the Coriolis Effect into the account, it would deviate. And this deviation you should account depending on what kind of analysis and what kind of gadgets that you want to devise.



So, it influences over very large distances. You cannot ignore Coriolis Effect.

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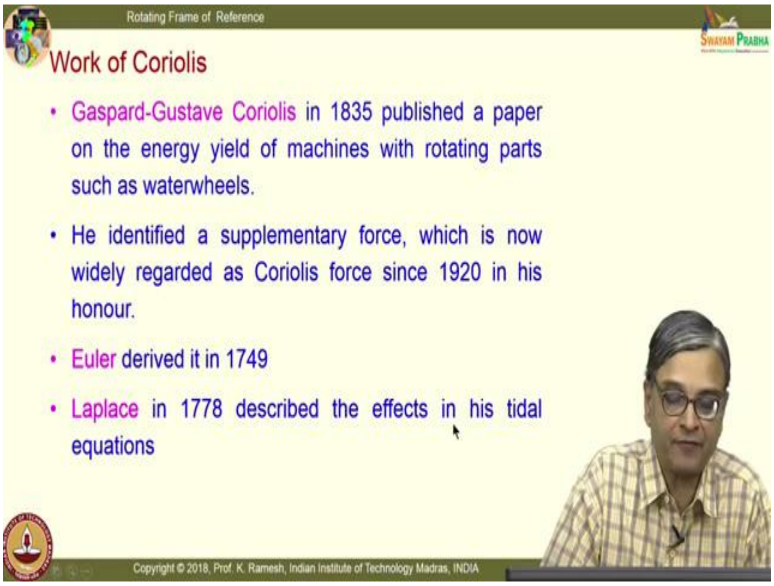
And if you go back to historical development, the discussion of geocentric versus heliocentric is also wedded to the development of Coriolis Effect. Way back in 1651 Italian scientist Riccioli and his assistant Grimaldi predicted that a cannon ball fired to the north to deflect to the east.

This is a very right prediction provided the earth was rotating. And another scientist in 1674, Milliet Dechales described how falling bodies and projectiles aimed toward one of the planet's poles would deflect due to earth's rotation. We have seen the following bodies also deflect. And we have also understood reasonably well due to earth's rotation, how do you see the winds change its direction. And you should note that although, their predictions are truly scientific, they used it for defending geocentric theory.

See, here you have to recognize, in those days there was no clarity on what is the shape of the earth, whether it is rotating, whether we are in the geocentric theory is acceptable or heliocentric theory is the most appropriate theory. This debate was still on in the western world. And since they were passionately attached to geocentric theory, as there was no proof available, they used these affairs because there is no proof available from experiments. They argued that these effects are not observable and earth is immobile, thus refuting Copernicus's heliocentric theory.

It may look folly now. But, in those days, even scientific discovery, truly scientific in nature, was not possible to be interpreted in the right light because of lack of peripheral knowledge. Now, we have satellite imagery you can take a picture of the cyclone and see whether it is rotating anticlockwise or clockwise. So, all this information is available now to verify what we predict from theory.



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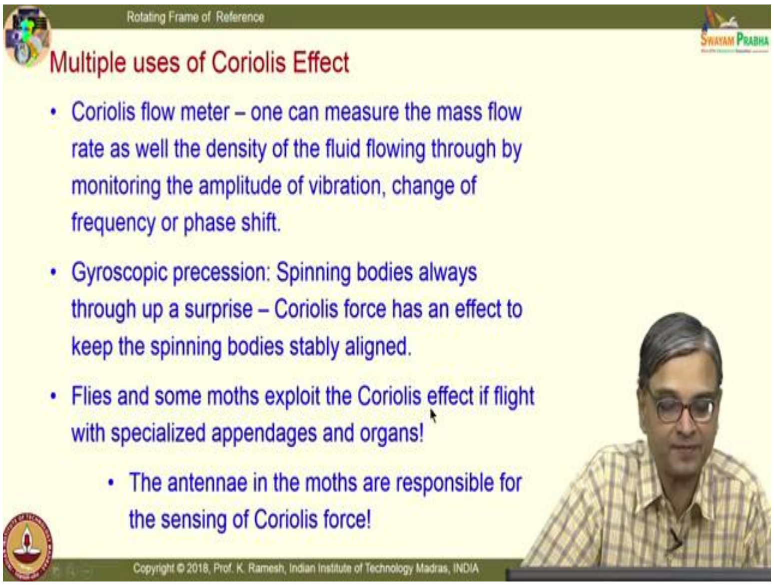
And if you look at the history, it was in 1835, the French scientist Gustave Coriolis published a paper on the energy yield of machines with rotating parts such as waterwheels. His observation was, there was a supplementary force, which is now widely recognized as Coriolis force since 1920 in his honor. And if we look at the mathematical derivation by Euler, it was available in 1749 itself. Laplace also had it in 1778 while he described the effects on tidal equations.



However, there was no clarity on understanding these concepts at that point in time. It all became popular only after the work of Coriolis.

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And there are also multiple uses of Coriolis Effect. You also have a Coriolis flow meter. And what you have here is essentially because of the fluid flow and the Coriolis Effect the probe will oscillate like this. So, they measure the frequency, they measure the amplitude of vibration or a phase shift. Using this they were available to devise a methodology to estimate the mass flow rate as well as the density of the fluid flowing through the tube. You know, normally, physicists exploit any new physical principal to make it as a measurement usage for a particular application.

So, that is how Coriolis flow meter came into existence. And you will also be surprised that people use it for gyroscopic precession in a very positive way. Spinning bodies always through up a surprise, Coriolis force has an effect to keep the spinning bodies stably aligned. So, this is used for inertial stability and so on and so forth. And you know, with great struggle, human civilization as understood what is Coriolis Effect and how it can be used.

There were confusions in understanding out of this. There was also confusion in, even though the predictions were correct, they were not able to associate with heliocentric theory at that point in time. In fact, since they were passionately attached to geocentric theory, they use this as an argument to say the earth was immobile. How folly it is. But if you go to nature, we have altogether a surprise.

We had so much struggle to understand Coriolis Effect. You find flies and some moths exploit the Coriolis Effect in flight with specialized appendages and organs.

It is very surprising. And all your drones, they are taking inspiration from insect flight. And insect flight is not very simple, it is extremely complicated dynamically. The antennae in the moths are responsible for the sensing of Coriolis force. How sophisticated nature in comparison to human evolution? So, we have to be really humble to accept this.

So, in this lecture we have looked at a deeper understanding of what is Coriolis acceleration. And we also learnt from a rotating frame of reference, how I would observe a ball that is thrown in a rotating platform which moves straight. But, sitting on a rotating platform I would observe that as deviating.

That knowledge is very important to appreciate some of the phenomena that we observe on earth. And you should recognize that earth is a rotating platform. Though it rotates slowly, it affects phenomena that happen over large distances. Like, you have cyclones the cyclones are influenced by Coriolis Effect. And we have also looked at briefly the historical development and also how nature is far ahead of all the scientists put together.

Thank you.