Engineering Mechanics

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Kinematics

Module 10 Lecture 25
Relative motion

Today, we are going to discuss about the relative motion. Motion of one particle with respect to the other particle. That can be described.

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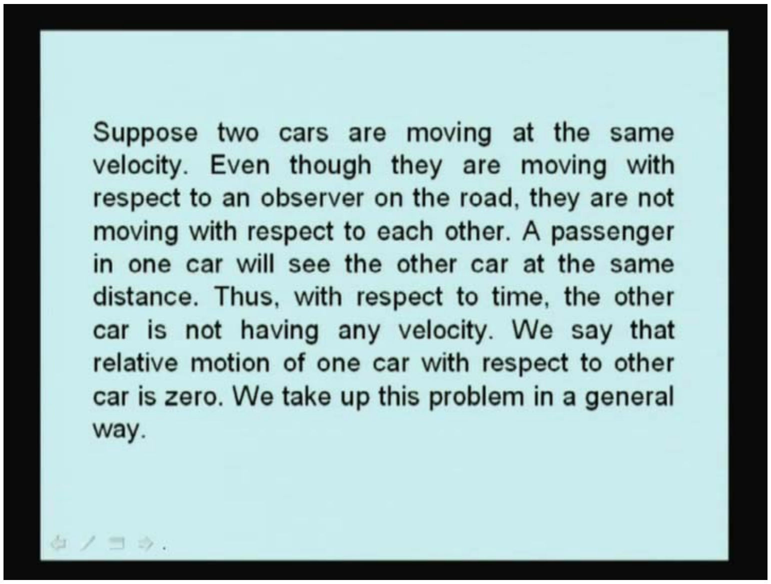

If you have two cars which are moving at the same velocity, even though they are moving with respect to an observer on the road, they are not moving with respect to each other. A passenger in one car will see the other car at the same distance. Thus, with respect to time, the other car is not having any velocity with respect to passenger in the car. We say that the relative motion of one car with respect to the other car is zero. We will discuss this problem in a more general way, when the cars may not move only in the straight line but they may be undergoing curvilinear motion.

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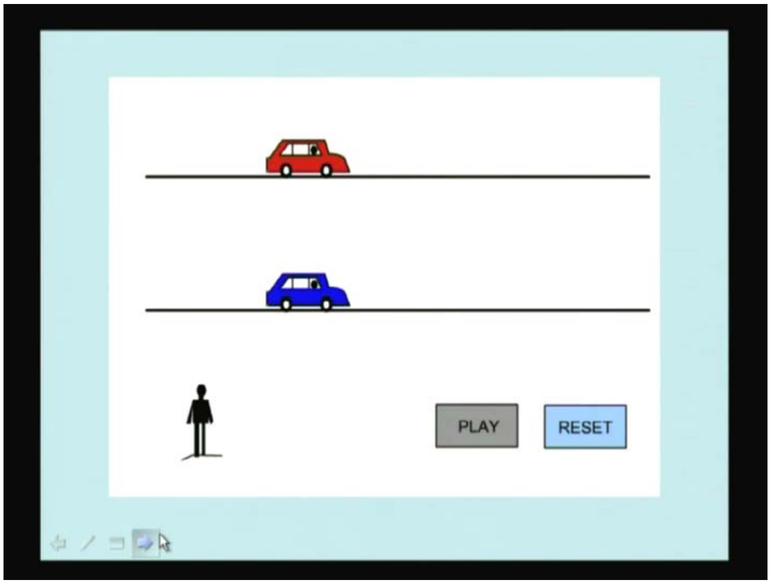

This is one animation showing the motion of two cars; red car and blue car. The driver in the red car always sees the blue car. Therefore, with respect to the red car, blue car is not having any relative motion.

However, drivers will come to know that they are moving at a high speed because they will see the other surrounding objects like, tree and all this. Outside the person is seeing that both the cars are moving with the same velocity. We are familiar with the concept of relative motion. In train also, sometimes we get the illusion that the train is moving because the other adjacent car starts moving, but when we see other objects like poles etc., we get the idea that it is our train which is not moving. In a way, we attach one axis system in our mind.

When we observe the objects moving, we have some reference frame; in that reference frame, we study its motion. Therefore, this lecture can be considered about expressing the displacement, velocity and acceleration with respect to particular coordinate system. Those coordinate systems, itself maybe translating with respect to another coordinate system or it may be rotating. Imagine that a boy is revolving a rod in a horizontal plane in the circular path. Now, if a particle is situated at the middle of the rod and another particle is at the end of the rod, then the particle which is at the middle of the rod will always see the particle at the end of the rod. Therefore, what happens, it may be observed that the particle is not having any relative motion with respect to this; however, from outside, we observe that both the particles are having different velocities. Particle, which is at the end of the rod moves with a higher velocity compared to the particle which is at the middle. Therefore, there is a relative motion between the two particles.

However, we have taken its rotating coordinate system and that is why the middle particle does not observe the velocity of the particle at the end.

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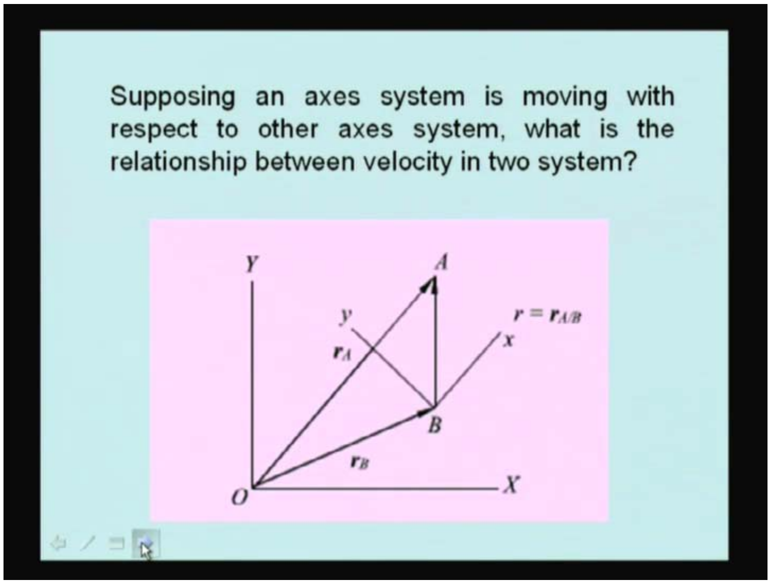

Therefore, it all depends on what type of axes system we have chosen. Here, in this figure, O X and Y are the axes system shown. One particular particle, a point is indicated by B; r_B is the position vector. This is A; another point A. r_A is the position vector. If we fix a coordinate system, you can consider that B may be one particle and A, the other particle. Both may have different velocities.

If we fix up another coordinate system attached to the particle B which is indicated by x and y, in the most general form, it can have this thing. Supposing an axes system is moving with respect to the other axes system; that means x-y is moving with respect to another axes system that is Ox and Oy system, X-Y system, then what is the relationship between velocities in two systems?

The difference between these two position vectors r_A and r_B is indicated by another vector that is called BA, r_B plus BA gives you $r_{A;}$ or, we can write r is equal to r_A with respect to B. This is the position vector of A with respect to B, which is indicated by r.

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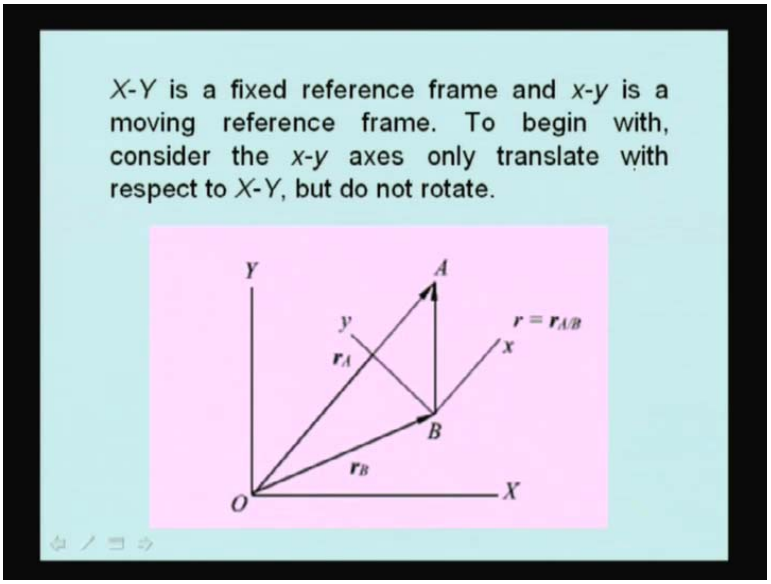

We have already mentioned that X-Y is a fixed reference frame and x-y is a moving reference frame. To begin with, we consider that x-y axes only translate with respect to X-Y, but they do not rotate. In previous examples, one car is translating with respect to the other car, but it is not rotating because they all moving in a straight line path.

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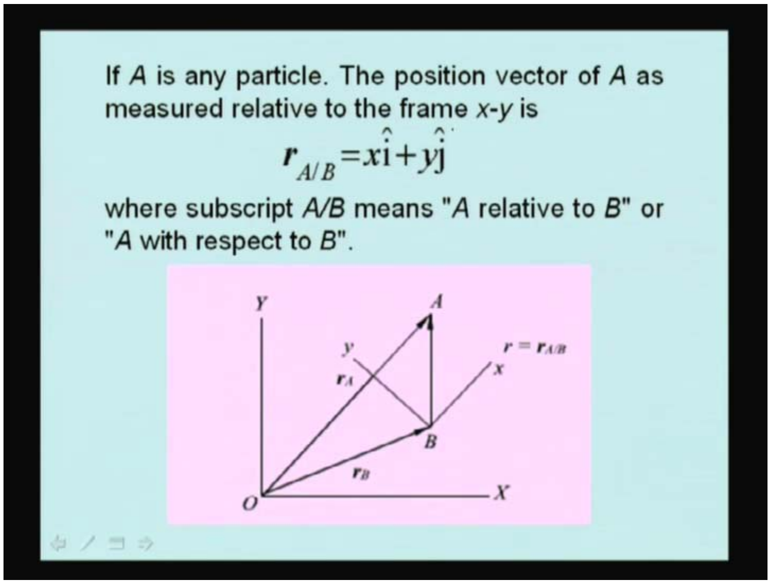

This case becomes quite simple; if A is any particle, the position vector of A as measured relative to the frame x-y is $r_{A/B}$ is equal to xi plus yj, where subscript A slash B means A relative to B or A with respect to B. X Y are the components of the position vector and they have been expressed here in terms of the unit vectors in the frame X-Y.

We may have adapted unit vectors in the fixed reference frame, that means we could have such that I hat and J hat. However, it is known that if the axes are parallel to each other, if x is parallel to y, in that case I hat will be equal to i hat. In this case, we have expressed it xi hat plus yj hat.

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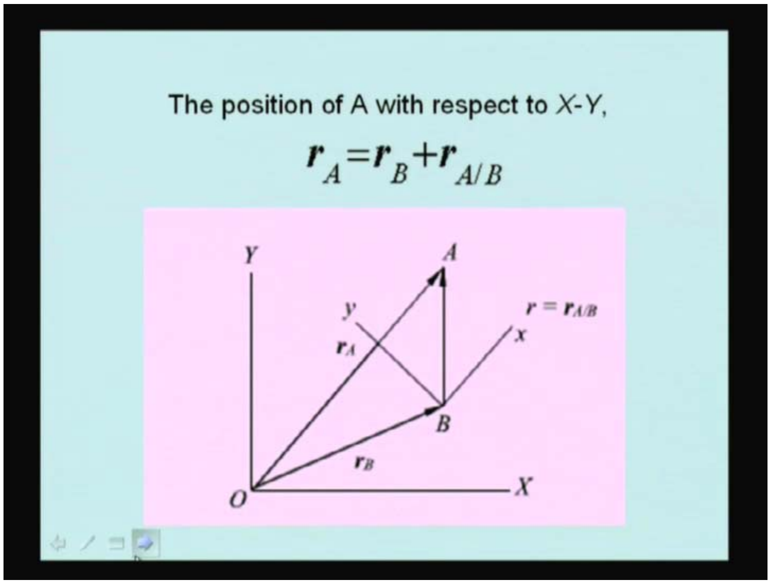

The position vector of A with respect to X-Y is given by r_A is equal to r_B plus $r_{A/B,}$ A with respect to B. With this, we can differentiate this position vector with respect to time because we know, we have some idea about vector calculus; vectors can be differentiated.

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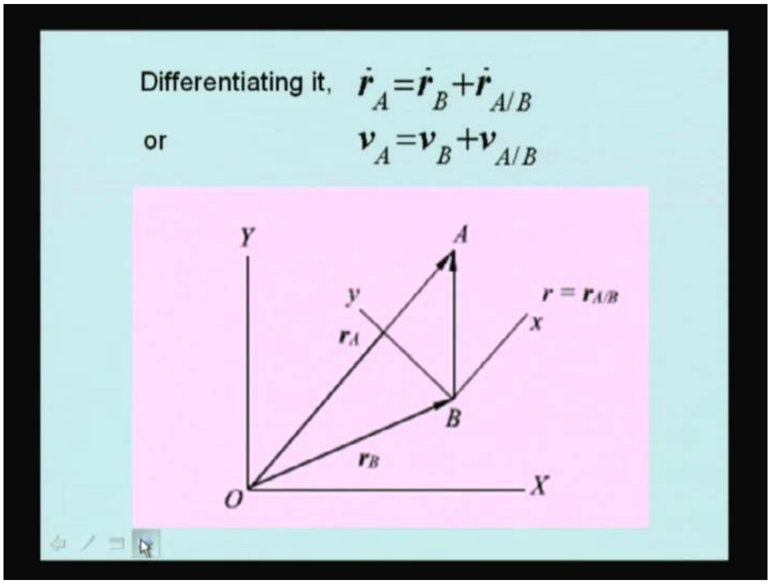

Differentiating it with respect to time and indicating the differentiation with respect to time by dot, we get r dot $_A$ equal to r dot $_B$ plus r dot $_{A/B}$ or r dot $_A$ is nothing but the velocity of A change in the position vector of A because r_A is the position vector with respect to OXY frame, X Y frame. Therefore, r dot_A gives the absolute velocity of point A; that is indicated by v_A.

Similarly, r_B is the position vector of B in X-Y reference frame. Therefore, r dot $_B$ indicates the velocity of point B that is absolute velocity B plus v_A with respect to B because $r_{A\ /B}$ is the position vector of A with respect to B. Therefore, r dot AB will be velocity of A with respect to B. Therefore, we get a simple relation that v_A is equal to v_B plus $v_{A\ /B;}$ that means velocity of particle A is equal to velocity of particle B plus velocity of particle A with respect to B.

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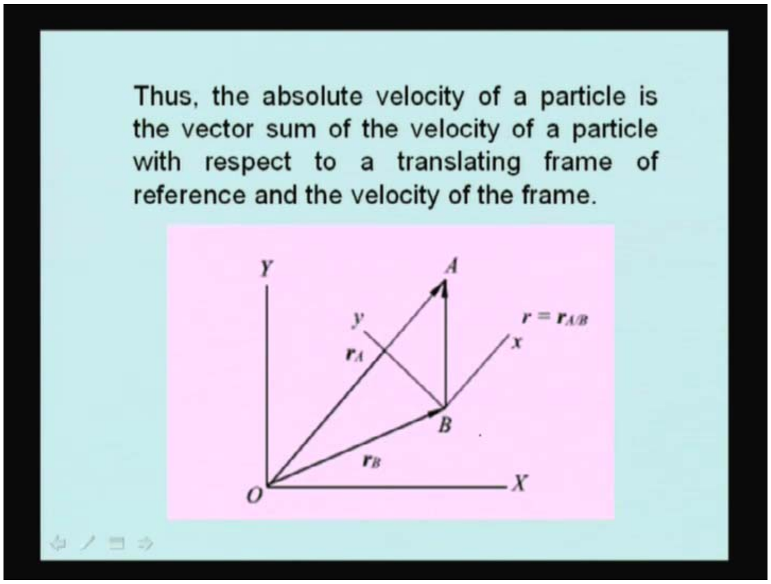

Therefore, absolute velocity of a particle is the vector sum of the velocity of a particle with respect to a translating frame of reference and the velocity of the frame itself. If we say velocity of the frame because frame is attached at B, v_B can be called as the velocity of the frame and v_{AB} can be called velocity of the particle A with respect to this translating frame which is attached at particle B.

We need not mention again about that there is a particle B. Instead, we mention that there is a particle A, whose velocity is measured with respect to a reference frame which is moving. Reference frame origin is indicated by B; B may be physical particle or may not be particle.

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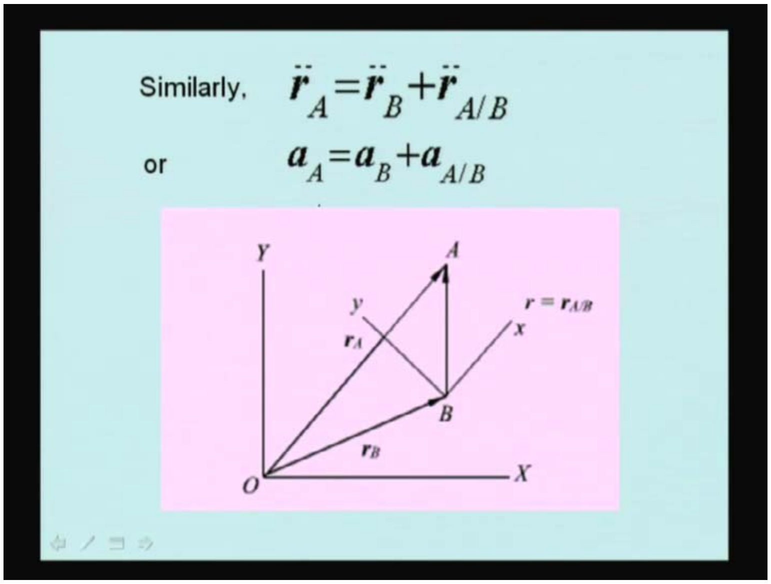

In the same way, we can find out accelerations. We take the double derivative, which we indicate by double dot or the vectors. r double dot $_A$ is equal to r double dot $_B$ plus r double dot $_{A/B}$ or a_A is equal to a_B plus a with $_{A/B}$.

Here, in this case, a_A is the absolute velocity absolute acceleration of point A, a_B is the absolute acceleration of point B and $a_{A/B}$ is the acceleration of point A with respect to point B in the reference frame which is moving.

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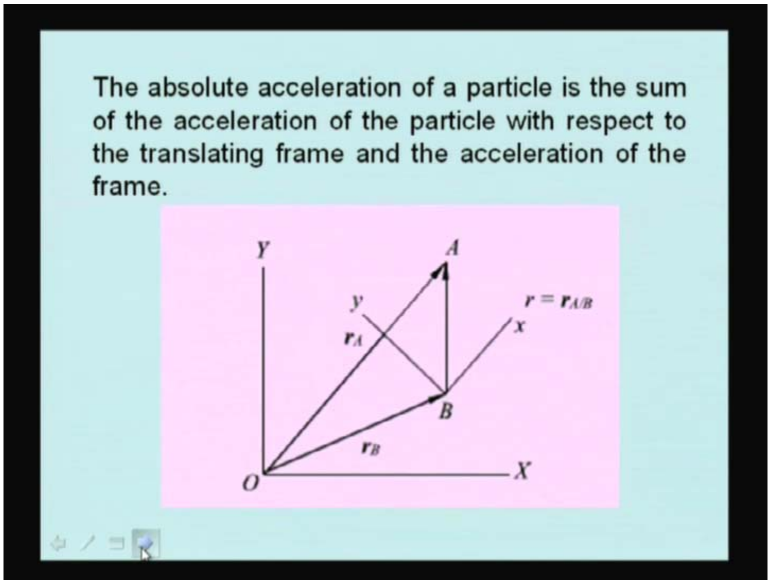

Thus, the absolute acceleration of a particle is the sum of the acceleration of the particle with respect to the translating frame and the acceleration of the frame itself. Because we can see that a_B is the acceleration of the frame; that means, a_B is the acceleration of the origin of the moving reference frame.

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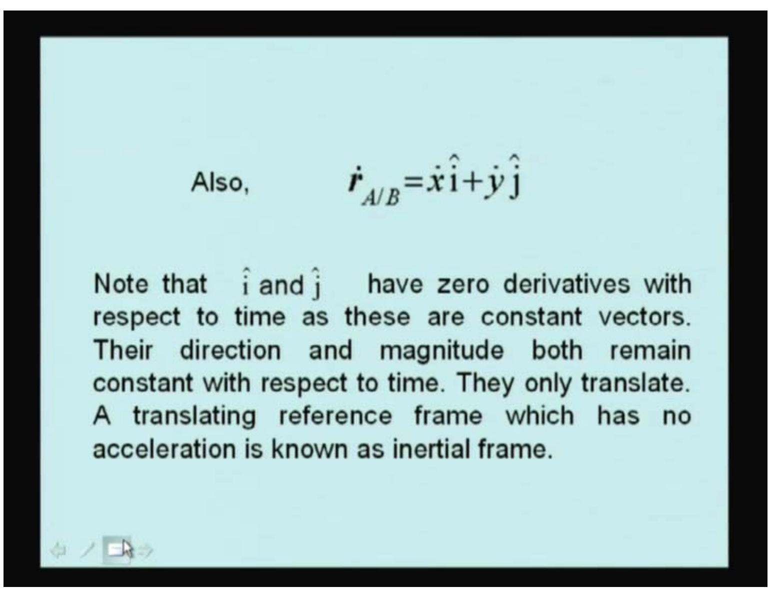

Also, in the component form, r $dot_{A/B}$ which is the velocity of A with respect to moving reference frame; that can be written as x dot i plus y dot j. Note that i and j have 0 derivatives with respect to time, as these are constant vectors. In translating motion, i and j does not change with time. Their direction and magnitude both remain constant with respect to time.

A translating reference frame which has no acceleration is known as inertial frame. If a translating reference frame is having acceleration, it is known as non-inertial frame. A rotating reference frame cannot be an inertial frame. An inertial frame is that reference frame which is translating with respect to the other reference frame with constant velocity.

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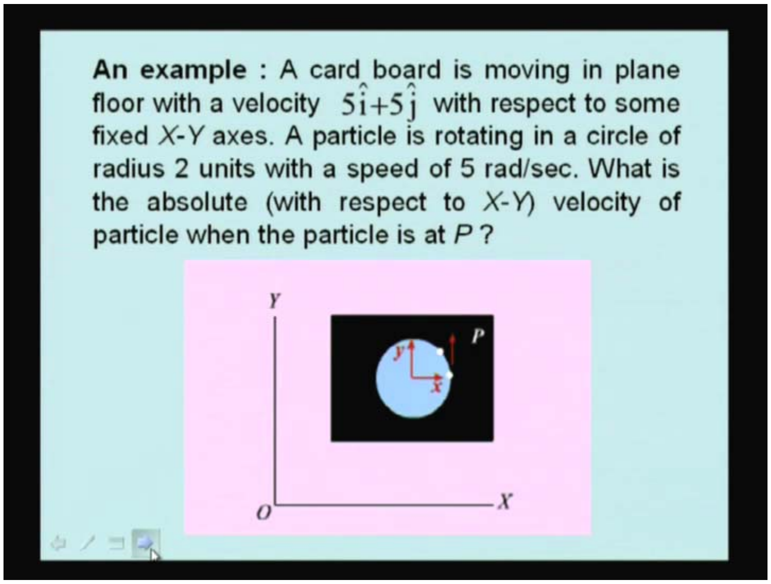

We present one example of using these relations. In this figure X-Y system is shown; that is fixed reference frame. In this frame, a cardboard is moving in this plane floor with a velocity 5 i plus 5 j with respect to fixed X-Y axes.

In this cardboard which is black cardboard, a particle is rotating in a circle of radius 2 units with an angular speed of 5 radian per second. Question is what is the absolute velocity of particle with respect to X-Y frame, when the particle is at point P? This is the velocity of the particle P and that has been shown here.

We can attach an axes system x-y which is translating with respect to X-Y, this moving axis system has been indicated by red lines.

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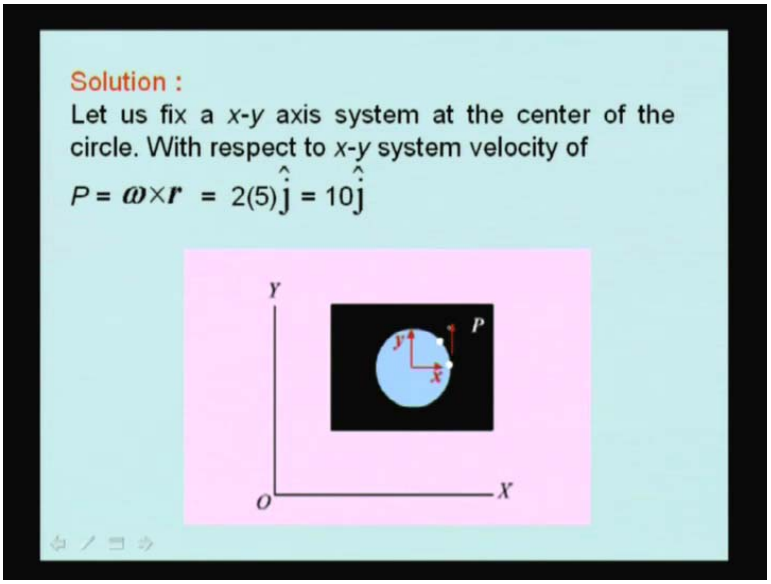

Fixing the x-y axis system at the center of circle with respect to X-Y system, velocity of point P is given by omega cross r; that means omega is mentioned, that is r is 2 units and omega is 5 radian per second. This is 2 into 2 into 5j; that means it comes out to be 10j unit, 10j.

We have to notice that this small j is the unit vector in the moving reference frame. This small j is in the moving reference frame. We could have said capital J also; of course in this particular case capital J will be same as small j. One has to always pay attention that in which system is he expressing the unit vector. So, with respect to X-Y system velocity of point B has been specified as 10j.

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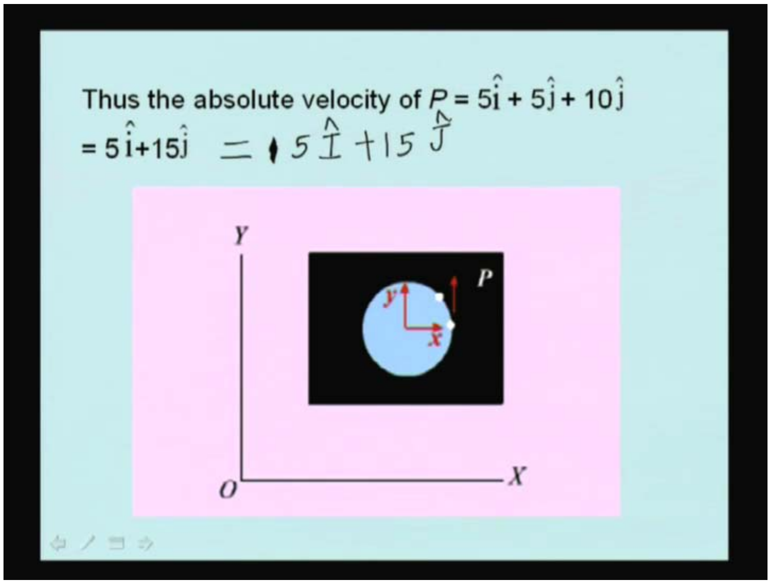

Thus, the absolute velocity of P is equal to the velocity of the reference frame itself plus the velocity of the particle in that reference frame. It has been already mentioned that the cardboard is moving in a plane floor with a velocity 5i plus 5j; that means the reference frame which is attached with the cardboard is having the velocity 5i plus 5j. Therefore, absolute velocity of P is 5i plus 5j plus 10j that is equal to 5i plus 15j.

One has to notice that although I am talking about the absolute velocity of particle B, however the answer has been expressed in terms of the unit vector in the moving reference frame. If one can write final answer in this manner also which is also very correct. 5I plus 15J, where I and J may indicate the unit vectors in the absolute reference frame.

However, it is not so important to always express the absolute velocity in the absolute coordinate system. Any coordinate system can be adapted. Only thing that one has to understand is that in which coordinate system the components have been expressed.

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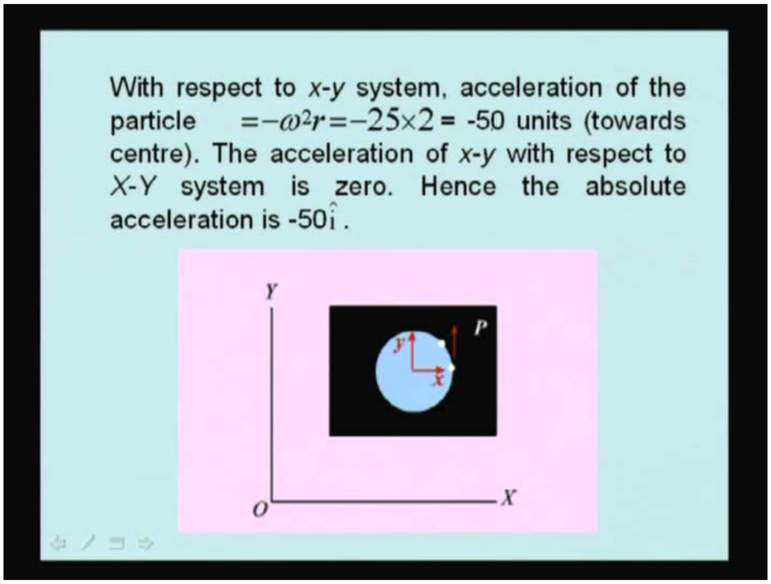

Now, we discuss about the acceleration of the particle with respect to x-y system; that means with respect to moving coordinate system. Acceleration of the particle is equal to minus omega square r. We have used minus term. It is directed at the momentum and it is directed towards the negative x direction. Therefore, this is equal to minus 25 into 2 omega is equal to 5 radian per second, r is equal to 2 units; this becomes minus 50 units towards center.

The acceleration of x-y that means 50 units towards center that is why minus 50 sign. The acceleration of x-y with respect to X-Y system is 0 because the cardboard is moving with a constant velocity. Hence, the absolute acceleration is minus 5i itself.

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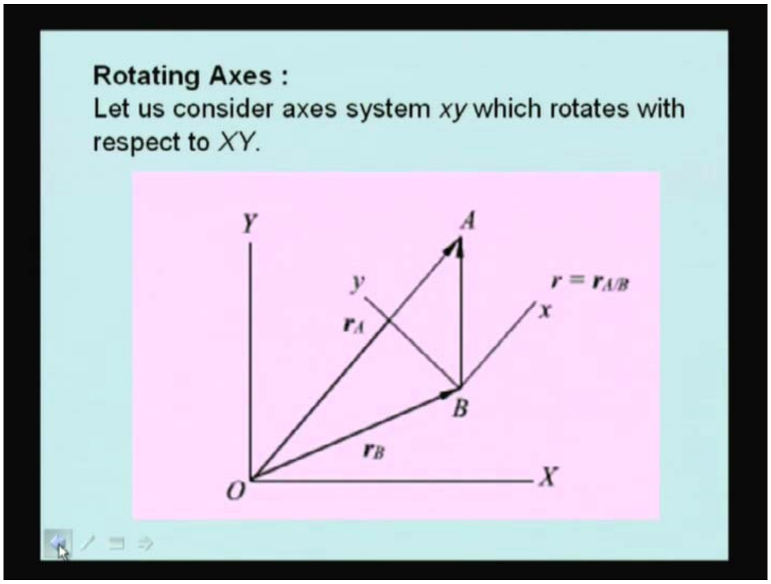

We discuss the rotating axes system. Let us consider axes system xy which rotates with respect XY system. Again the same figure; here also, the same relation is valid that r_A is equal to r_B plus r_{AB}. That relation remains same whether this coordinate system is moving, translating or rotating.

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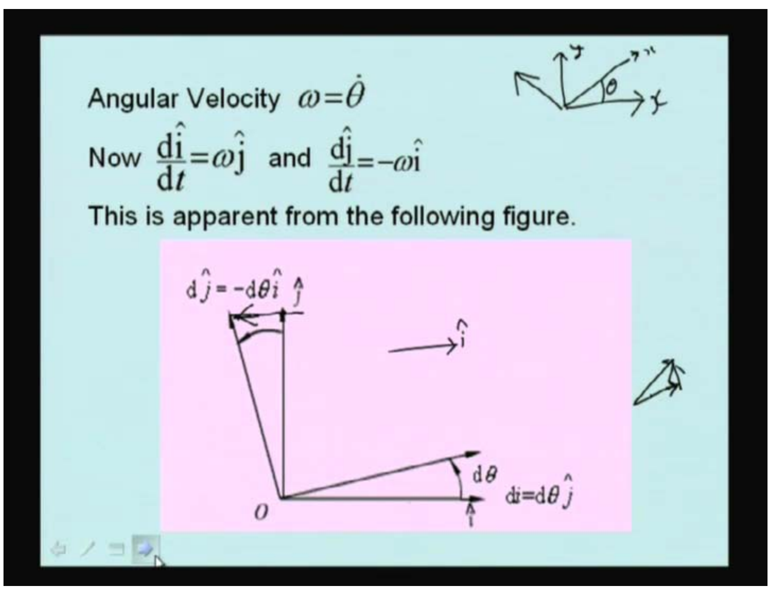

We also define that the angular velocity of the rotating axis is omega, where omega is equal to theta dot; that means d theta dt. We have the axis x; y rotates by an amount theta. Because it is rotating, this theta can be differentiated with respect to time.

We can easily see that if the unit vectors i and j are expressed in the moving coordinate system; that means rotating coordinate system, then di by dt will be omega times j and dj by dt is equal to minus omega times A.

In the translating reference frame, di by dt was 0; however, in the rotating reference frame, di by dt will not be 0 because the vector is although it is maintaining the same magnitude, it is rotating; that means it is changing the direction. This is apparent from this figure.

Here, the unit vector i has rotated by an amount d theta. Therefore, there is a change in the position of the vector. If this is the vector, after d theta time this vector before their difference is indicated by another vector and this magnitude will be equal to d theta. Because these are this one. It will be in the j direction because in the unit d theta tends to 0, di approaches the ji direction. Therefore, if we differentiate di with time, we get d theta by dt that is omega times j.

Similarly, the vector j has rotated to a new position. Therefore, dj will be directed towards this side. This is dj and its magnitude is naturally a unit vector, it is d theta dj, but it is in the minus direction of i because positive i is this direction. Therefore, it is minus d theta into j, dj is equal to minus d theta into i.

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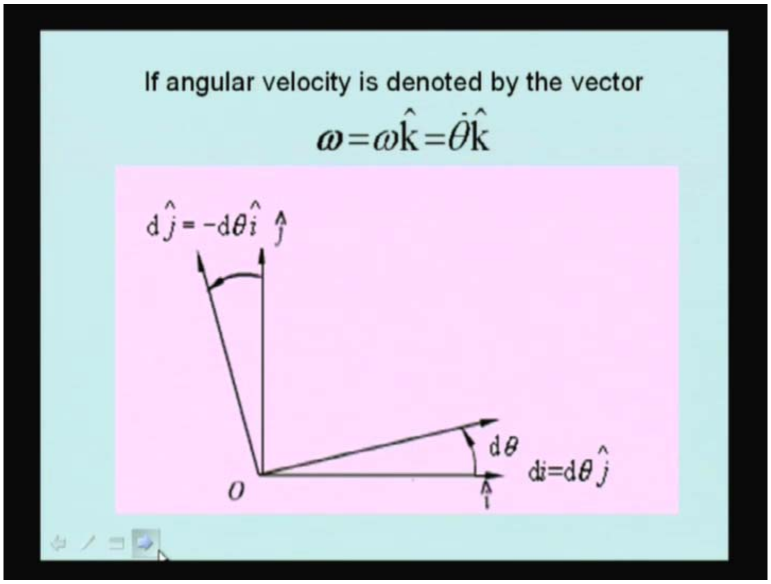

If angular velocity is denoted by the vector, that is omega is equal to omega k hat, that is d theta by dt or theta dot multiplied by k hat, k hat is the unit vector and it is along the z direction that is normal to the plane.

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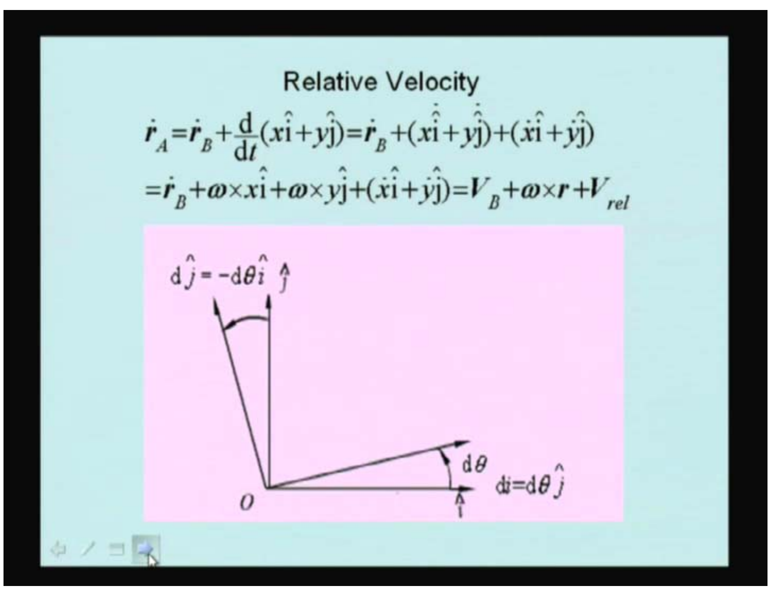

Then we can also write that omega di by dt is omega cross i; like that dj by dt is also omega cross j. Relative velocity of the point A with respect to moving frame x-y can be found by differentiating the basic relation r_A is equal to $r_{B\ plus}$ $r_{AB;}$ differentiating it with respect to time, we get r dot $_A$ is equal to r dot $_B$ plus d by dt xi plus yj is equal to r dot $_{B.}$ Differentiating xi with respect to time, we get one term x into i dot plus x dot into i. Then, we get y times j dot plus y dot j.

In this case, i dot is not equal to 0; instead i dot is given by omega cross i. Therefore we get, r dot $_B$ plus omega cross xi plus omega cross yj plus x dot i plus y dot j. omega cross omega can be taken common and it will become omega bracket xi plus yj which gives V_B plus omega cross r plus x dot i plus y dot j can be called as relative. Because this is the velocity of the point A in the frame of reference, moving reference frame, that is the relative velocity here; because position vector is xy, that means relative.

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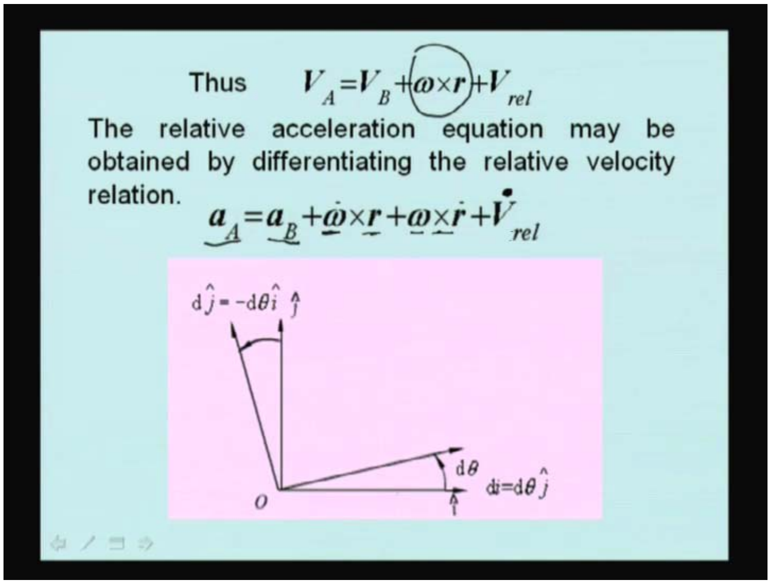

Thus, we get a relation that is V_A is equal to V_B plus omega cross r plus $V_{rel.}$ We get one extra component; in this case it is not equal to V_A-V_B. Instead, we get one additional term which is important, that is omega cross r. If the reference frame is only translating, in that case omega becomes 0 or a translating reference frame omega is 0. Therefore, V_A is equal to V_B plus $V_{rel.}$ Likewise, we can find out the expressions for relative acceleration.

The relative acceleration equation may be obtained by differentiating these relative velocity relations. Relative velocity relation is given here; that is V_A is equal to V_B plus omega cross r plus $V_{rel.}$ Differentiate V_A with respect to time, you get a_A; differentiate V_B with respect to time you get $a_{B.}$ Differentiate omega r with respect to time, you get two terms because it is a cross product of two vectors. One is given by omega dot into cross product r plus omega cross product r dot. Differentiate V_{rel} with respect to time, you get $V_{rel,}$ that is differentiation of V_{rel} with respect to time.

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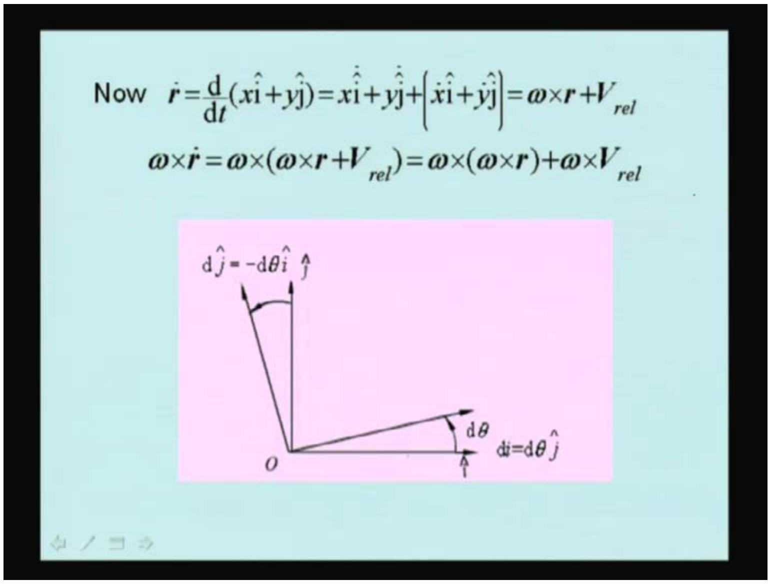

It is known that r dot, in this previous expression we got a term - r dot. Let us see, what is r dot? r dot is d by dt xi plus yj which can be written as xi plus yj plus xi dot plus yj dot plus x dot i plus y dot j. x can be written as omega cross r plus V_{rel} - this relation we have derived. Therefore, omega cross r dot can be written as omega cross bracket omega cross r plus V_{rel} which is equal to omega cross bracket omega cross r bracket close plus omega cross V_{rel}.

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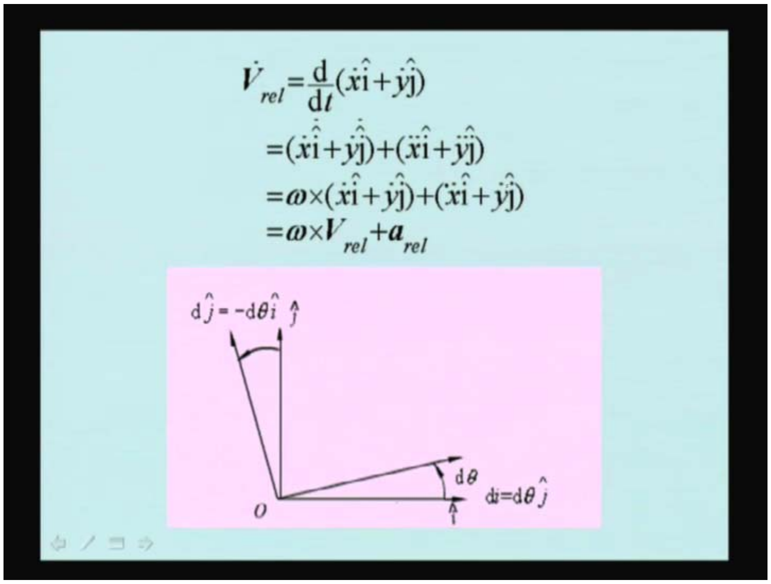

Now, V dot $_{rel}$ is basically d by dt x dot i plus y dot j, which can be written as x dot i dot plus x plus y dot j dot plus x double dot i dot plus y double dot j dot; which is equal to omega cross x dot i hat plus y dot j hat plus x dot i hat plus y dot plus x double dot i hat plus y double dot j hat. It can be written as omega cross V_{rel} plus a_{rel}.

Here, again we observe that V dot $_{rel}$ is really not equal to $a_{rel.}$ Relative velocity, if you differentiate with respect to time, you do not get relative acceleration. We get one additional term as well, which is omega cross $V_{rel.}$ In the translating reference frame omega becomes 0. Therefore, V dot $_{rel}$ is equal to a_{rel}; that means in the translating reference frame, if you differentiate the relative velocity, you get the relative acceleration; but, the same thing is not to have the rotating reference frame.

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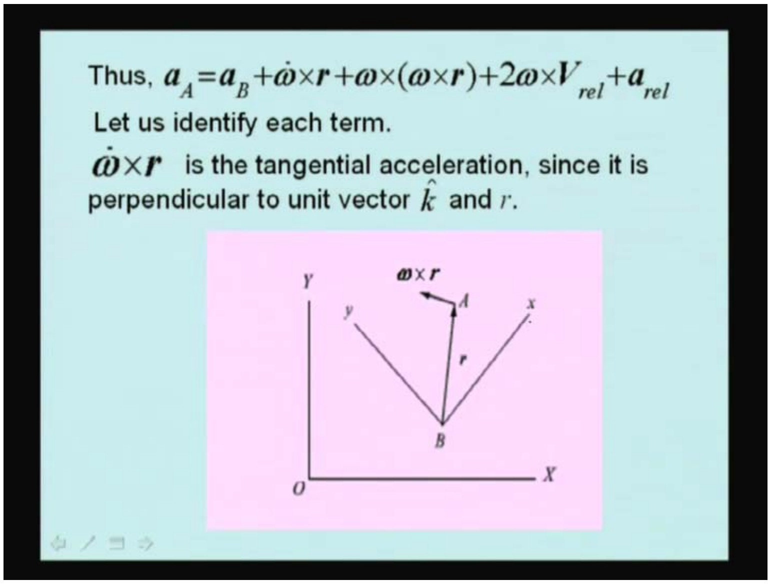

Thus a_A is equal to we get this big expression a_B plus omega dot r plus omega cross omega cross r plus 2 omega cross V_{rel} plus a_{rel}.

Let us identify each term in it. Omega cross r is the tangential acceleration. Since it is perpendicular to unit vector k and r, omega is having the direction k. Therefore, omega dot is also having the direction k. Omega cross is the vector which is in the tangential direction. This is shown here.

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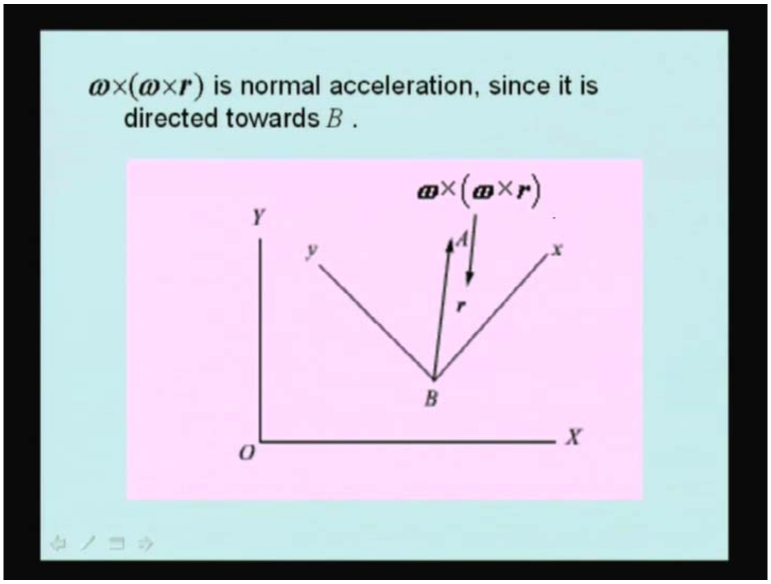

Omega cross omega r is normal acceleration since it is directed towards B. omega cross r will be towards j and j cross k again gives you i. This is towards B and this is called normal acceleration or the same thing as you get centripetal acceleration.

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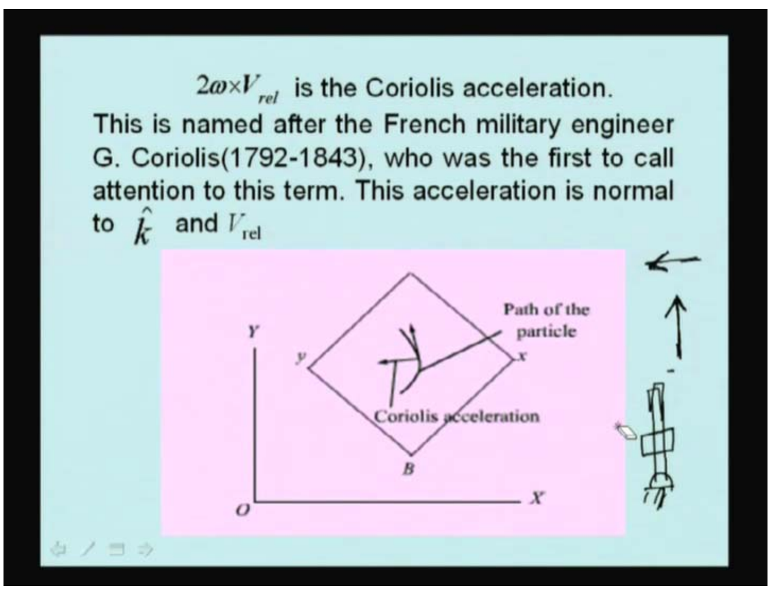

Now, 2 omega cross V_{rel} is the other term which we get in the expression for acceleration. 2 omega cross V_{rel} is really the Coriolis acceleration. This is named after the French military engineer G. Coriolis who was born in 1792 and died on 1843 who was the first person to call attention to this term. This acceleration is normal to k and V_{rel}.

If the particle is moving, if the path of the particle is like this and you have the relative velocity of the particle like this, rotate the relative velocity vector in the direction of the rotation; give a 90 degree turn and you get the direction of Coriolis acceleration. That means, if this is the relative velocity, suppose there is a link on which this slider is moving and linkage velocity like this; that means it is moving in the counter clockwise direction. Relative velocity of the slider is shown like this. We have to, because it is rotating in the counter clockwise direction, link itself is rotating in counter clockwise direction. Therefore, rotate the relative velocity in the counter clockwise direction. This is the direction of the Coriolis acceleration.

Similarly, if the rod would link, this would have been rotating in the opposite direction like this. Then, the Coriolis acceleration would have been like this. Coriolis acceleration can be in both the directions. Normal acceleration force is directed towards the center of the curvature.

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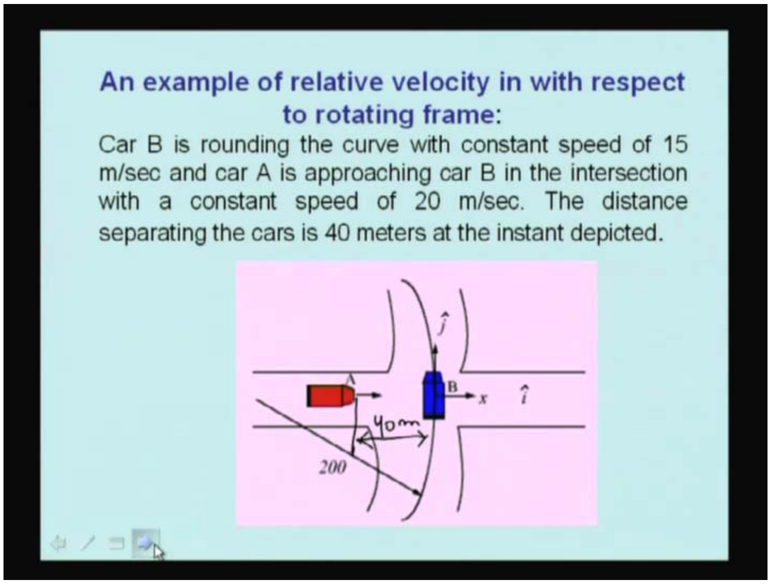

We will solve one example of relative velocity with respect to rotating frame. Let us consider this problem.

In this figure, there are two cars; blue car is moving on a circular path whose radius is of the curvature 200, the red car A is moving in a straight line and it is approaching B. So, car B is rounding with constant speed of 15 meter per second and car A is approaching car B in the intersection with a constant speed of 20 meter per second. The distance separating the cars is 40 meters at instant depicted. That means this distance is 40 meter. Size of the car is very small compared to the distance 40 meter. So, it can be treated as a particle.

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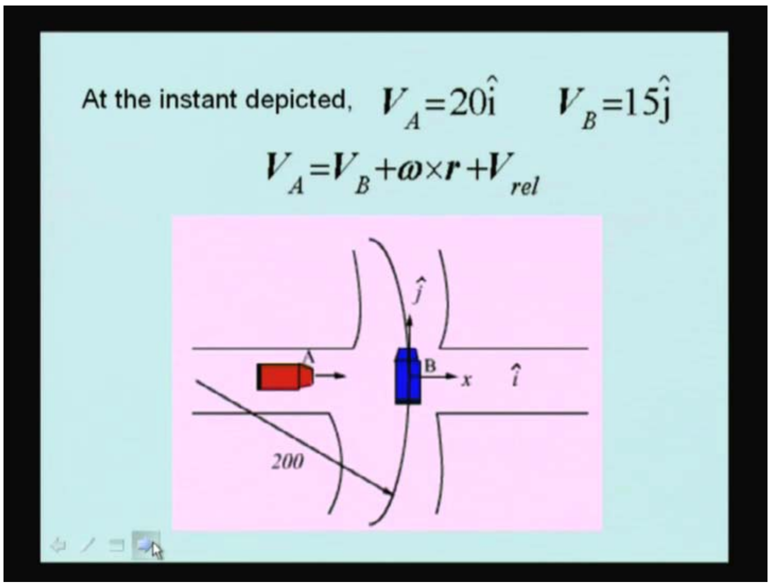

At the instant depicted, V_A is equal to 20i because it is mentioned that car A is approaching car B with a constant speed of 20 meter per second. Therefore, V_A comes out to be 20i.

V_B is moving with 15 meter per second on a circular path, at the instant depicted V_B will be equal to 15j. Apply the relative velocity formula; V_A is equal to V_B plus omega cross r plus V_{rel} are touching the moving reference frame in car B. Therefore, this is x unit vector is in the i direction that is i then yj. This reference frame is rotating on a circular path.

Therefore, velocity of A is given by velocity of B which is the velocity of the origin of the reference frame and that is same as, the velocity of the car plus omega cross r plus V_{rel} which is the velocity as seen in the moving reference frame or as seen by the driver in car B. Because the driver in car B is moving with respect to that reference frame.

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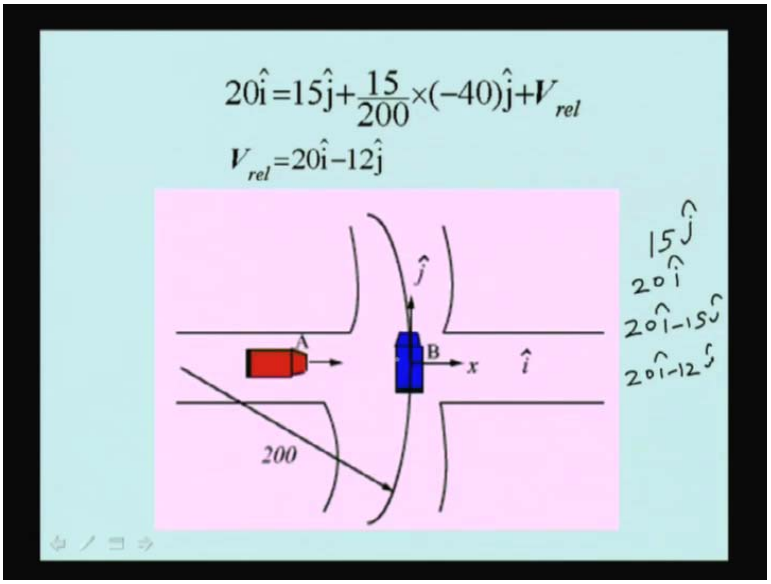

Putting the values, V_A is equal to 20i is equal to 15j plus 15 by 215, 15 by 200 is the omega cross minus 40j because minus plus V_{rel}. Therefore, solving this we get V_{rel} is equal to 20i minus 12j, this is the velocity of the car A as observed by the person sitting in car B. Remember, car B was having the velocity of 15j and car A was having the velocity 20 A; but, the relative velocity did not come 20i minus 15j instead it is coming 20i minus 12j. Had this car been moving in a straight line, then omega would have been 0. The velocity, the relative velocity would have come, instead of 20i minus 12j, it would have come 20 i minus 15j.

Therefore, see the difference a rotating coordinate system makes.

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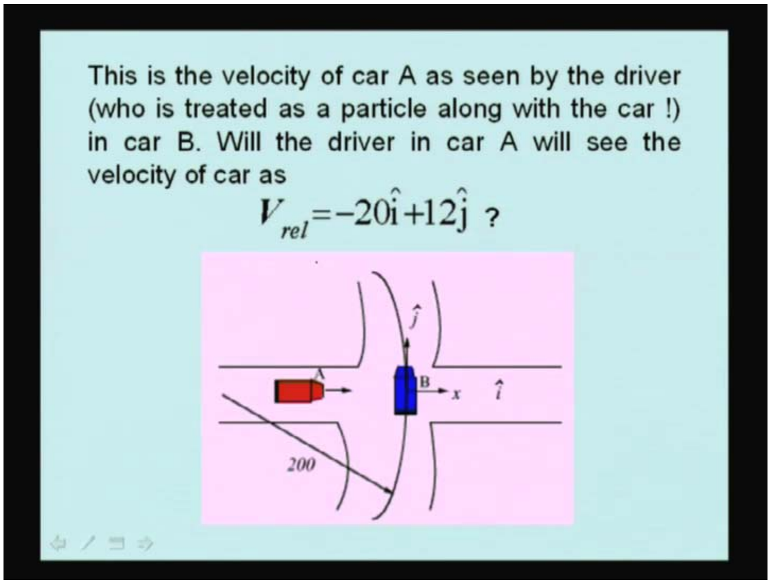

The velocity mentioned there is the velocity of car A as seen by the driver who is treated as a particle along with the car in car B. Will the driver in car A will see the velocity of car as V_{rel} is equal to minus 20i plus 12j? If the velocity of car A with respect to car B is 20i minus 12j then the velocity of car B with respect to velocity of car A is minus 20i plus 12j. No, we cannot say this.

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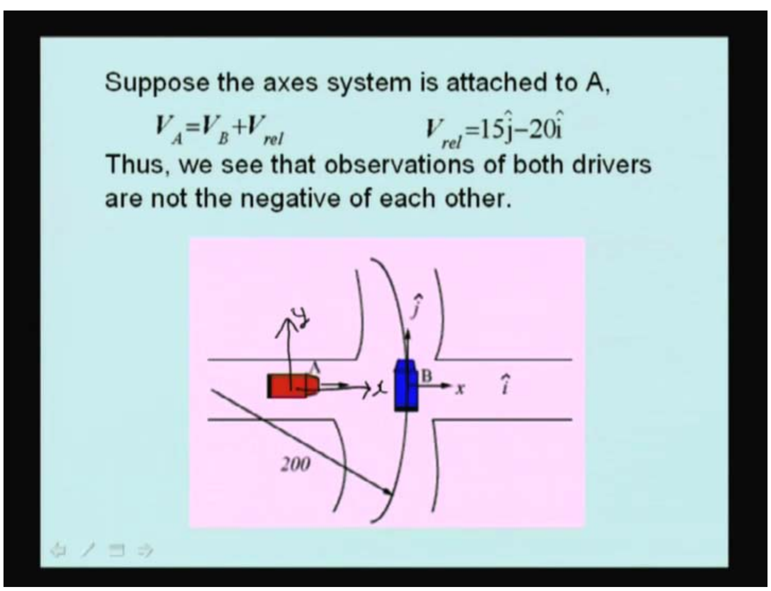

Let us see this thing. Suppose the axes system is attached to A, then V_A is equal to V_B plus $V_{rel.}$ In this case, the axis system is attached to this one. This axis system is not rotating, there is no omega; omega is 0. Therefore, the expression comes out to be V_A is equal to V_B plus V_{rel} or V_{rel} is equal to 15j minus 20i. Thus, we see that the observations of both drivers are not the negative of each other. That is this thing. Therefore, it is very important to understand these relations in translating as well as using reference frame.

Let us discuss some problems of the concepts developed.

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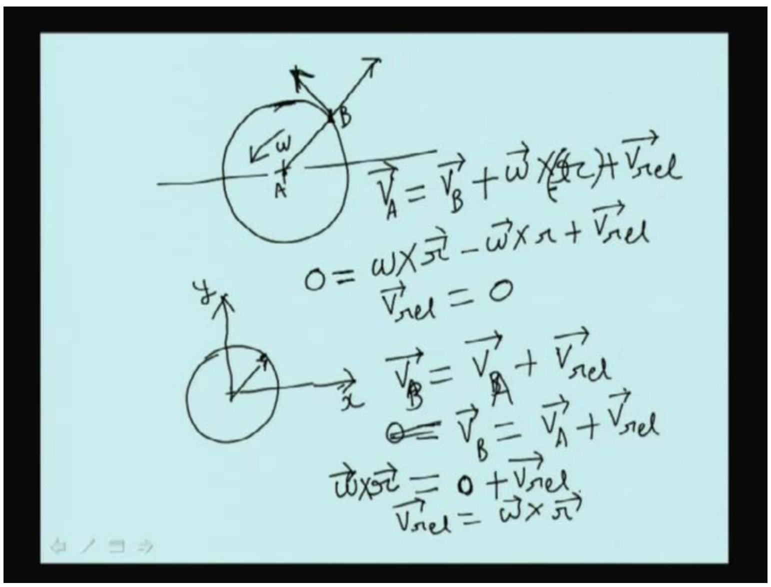

Now, imagine that a particle is moving. Particle is located at B; that is periphery of this one. The disc is rotating with an angular speed, omega. If we attach a moving reference frame at B, this is x radial direction, other is this one. Then, this frame of reference also rotates with velocity, omega.

In this case, V_B is equal to we get the relation, if we fix the coordinate system at A, V_A is equal to V_B plus omega cross omega cross minus omega cross r plus $V_{rel.}$ If A is a fixed point then V_A is equal to 0.

Now, in this case I have fixed an axes system here at omega cross r at this point. Therefore, I have to take this r as minus r, this is minus. Therefore, this is V_B and I can write V_B as omega cross r where r is the radius of the circle. This becomes omega cross r. This is minus omega cross r plus V_{rel} which gives us V_{rel} equal to 0; that means if a particle is placed at B and an axis system is attached with that particle, the particle will observe that center is at the same position and therefore you are getting V_{rel} is equal to 0.

However, if we fix up an nonmoving coordinate system here at particle A, then velocity of particle B, V are related with velocity of A in this fashion, V_A is equal to V_B plus V_{rel}, as the axis system is not rotating. Therefore, I am not putting omega.

Here, V_A is equal to 0 and this is V_B V_A plus $V_{rel.}$ Therefore, V_B is equal to V_A plus $V_{rel.}$ VB is known as omega r and V_A is equal to the tangential direction. This velocity is omega cross r. We can write in the vector form; omega cross r is equal to V_A that is 0 plus V_{rel}. Therefore, the relative velocity comes out to be omega cross r. That means, if you attach an axes system at point A then it will observe particle B to have relative velocity omega cross r.

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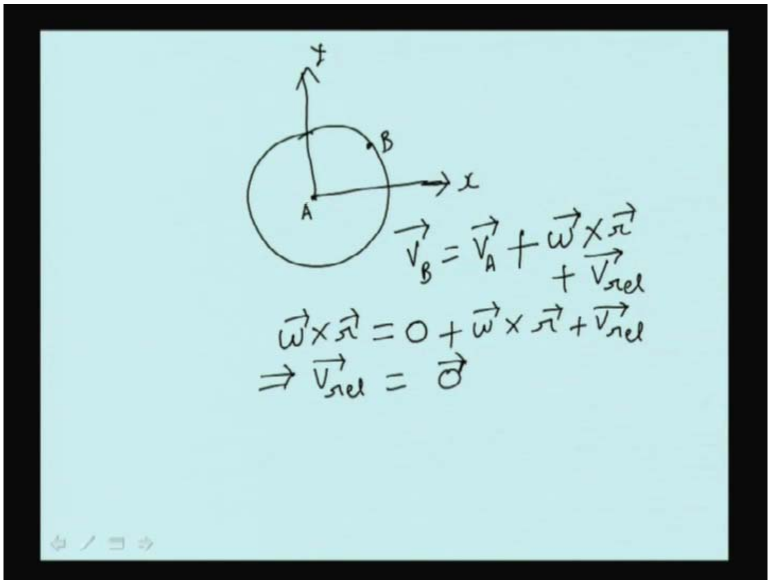

However, what happens, if the axis system is although attached with A, but unlike in the previous case it is not fixed. It is also moving with the disc. In that case, we have axes system which is having the velocity, omega.

Now consider a particle B here. The velocity B is equal to V_A plus omega cross r plus $V_{rel,}$ V_B in this case, is equal to omega cross r because absolute velocity is known to be omega cross r which is equal to 0 velocity plus omega cross r plus V_{rel}, which gives us V_{rel} equal to a 0 vector. Indicating that really it is not that, just particle is not enough. It is important what type of axis system has been chosen.

Same particle A may have the origin. One axis system was constant; not nonmoving. In that case, V_{rel} comes out to be omega cross r. If the axis system is also rotating with the disc, then V_{rel} turns out to be 0 which is inconsistent. As the axis system is rotating, it always follows particle B and thus, it is not able to know the difference in the position. We will discuss one problem concerning this principle.

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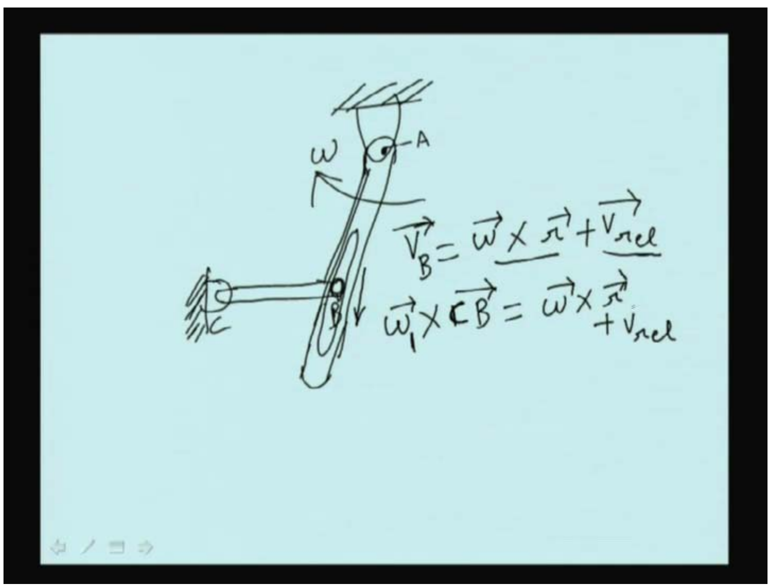

Here, this is link; link is there and this link is having a slot. On this slot, a ball is kept which can spin, which can slide and this is another link which is hinged here.

We may be asked to solve this problem. Given that you have the angular velocity omega and this point, that is point A; this point is point B. This is the point then this is point B. We have to find out the velocity of point B with respect to point A and also the angular rotation of this link which can be called as BC. Such type of problems also can be solved using the previous equation.

In this case, you can attach one axis system on this rod, which is rotating and then you can have V_A V_B is equal to V_A which is 0; that is omega cross r plus V_{rel}, At this stage, you know the relative velocity direction; that is direction is along this thing, but you do not know the magnitude at this stage. Omega, V_A is of course omega cross r; omega cross r can be easily calculated.

We have fixed up the axis system at point A; r is the radial the position vector of B with respect to A. Omega might have been specified to you. So, you will be able to calculate omega cross r plus and $V_{rel.}$ Only the direction is known. You do not know the magnitude, but then, we know the other equation that if you have the velocity of point B with respect to point C that is also this direction, has been given.

Absolute velocity of point B is omega cross BC omega cross vector CB velocity CB, which also has to be given. However, you do not know this is omega. I will indicate it by omega 1. Although you do not know that the magnitude of omega 1, you can equate this with this expression, omega cross r plus V_{rel} and you can find out $V_{rel.}$ We can express these in the component forms and then you can get two equations. There are two unknowns in this problem; one is the omega and other is the magnitude of $V_{rel.}$ That type of problem can be solved.

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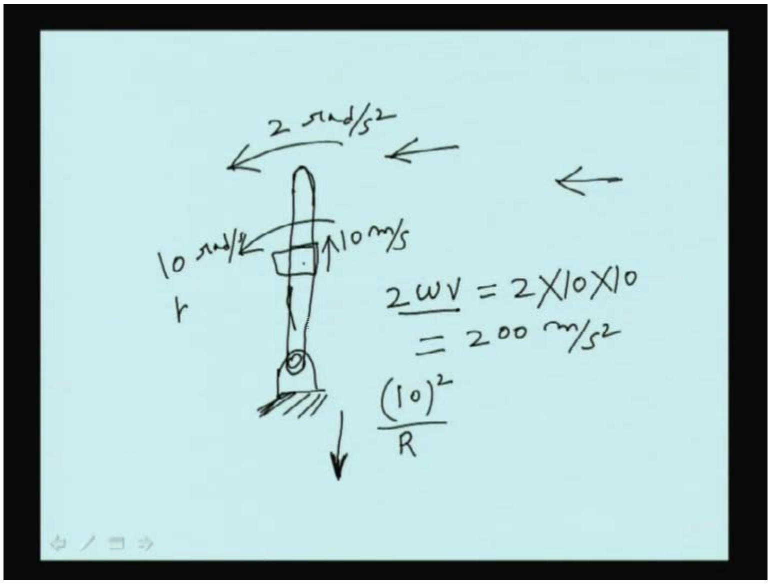

We will solve one simple problem of Coriolis acceleration. If there is a link here, which is rotating at10 radian per second and a particle is sliding at 10 meter per second, what is the Coriolis acceleration? Coriolis acceleration will be 2 omega into V. In this case, magnitude will be 2 omega V; that means, it will be 2 times 10 times 10, which will be equal to 200 meter per second square. Direction of this Coriolis acceleration will be in this direction. The Coriolis acceleration is not dependent on the position of the slider or the link. It is dependent on the relative velocity; however, there will be another component that is centripetal acceleration of this particle which will depend on the relative position. That is given by 10 square divided by r, where r is the distance of this. Therefore, this component decreases as the particle is 1.

This component is given in this direction. In this problem, the Coriolis will have the same direction as the tangential acceleration. If the tangential acceleration is provided and it is say 2 radian per Second Square, then the tangential acceleration will be in this direction and the magnitude will be alpha times r; that means this is 2 radian per second square multiplied by the distance is 1.

Like that, you can solve this number of problems using the equations developed in this case. Let me quickly summarize, what we have developed.

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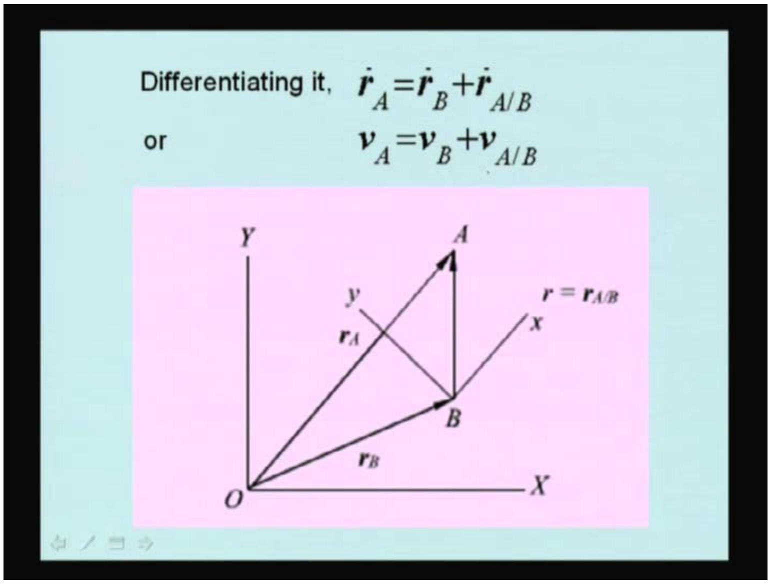

We started with translating reference frame and obtained the simple expression that is V_A is equal to V_B plus $V_{A/B}$.

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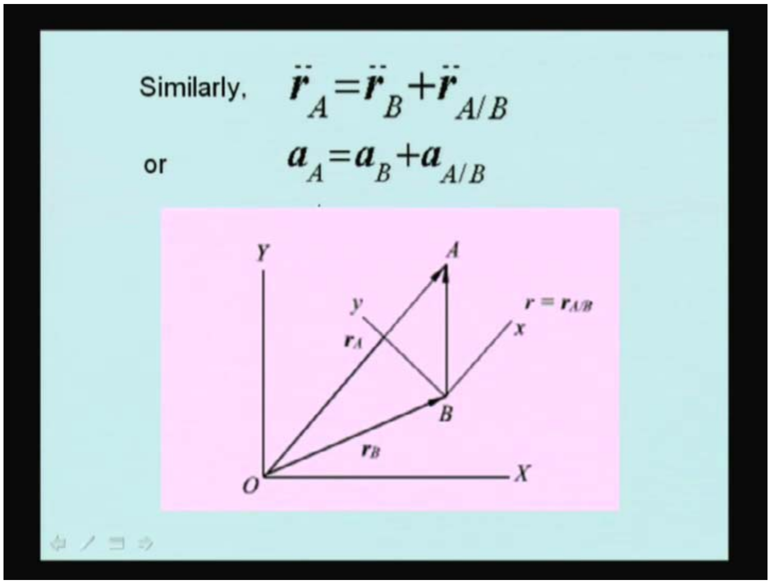

a_A is equal a_B plus $a_{A/B}$.

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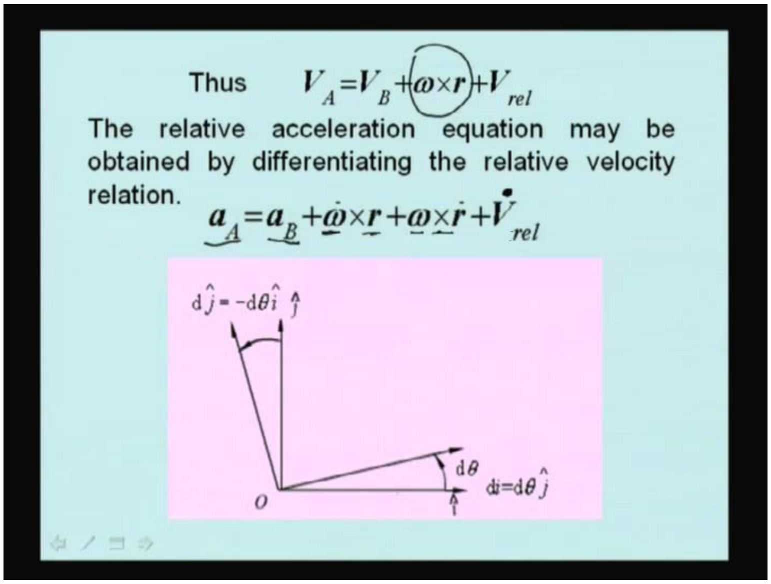

However, if the coordinate system is rotating, we get the equations V_A is equal to V_B plus omega cross r plus $V_{rel;}$ remember, there are three components here.

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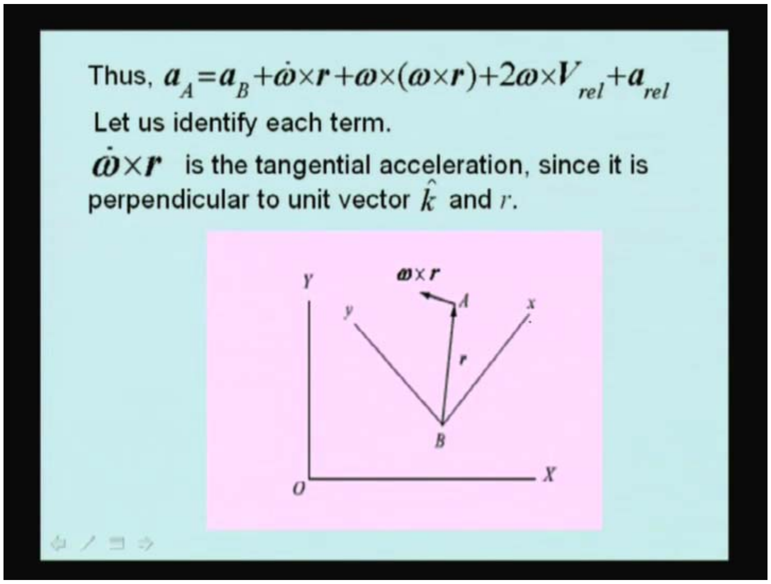

We get acceleration components, a_A is equal to a_B plus omega cross r plus 2 omega cross V_{rel} plus a_{rel}, Here we are getting 5 terms. These two equations are very important. In fact, in this expression, if you put omega is equal to 0, this equation reduces for the equation of the translating reference frame. Therefore, important equations are: one is this.

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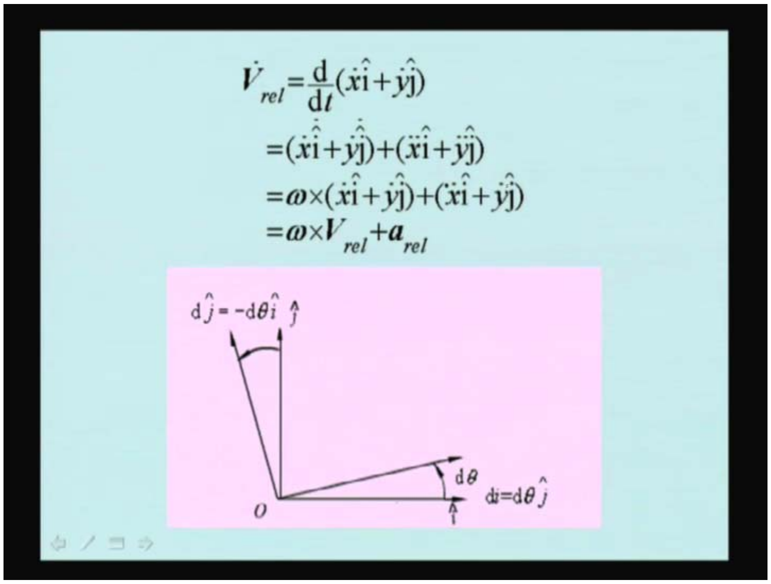

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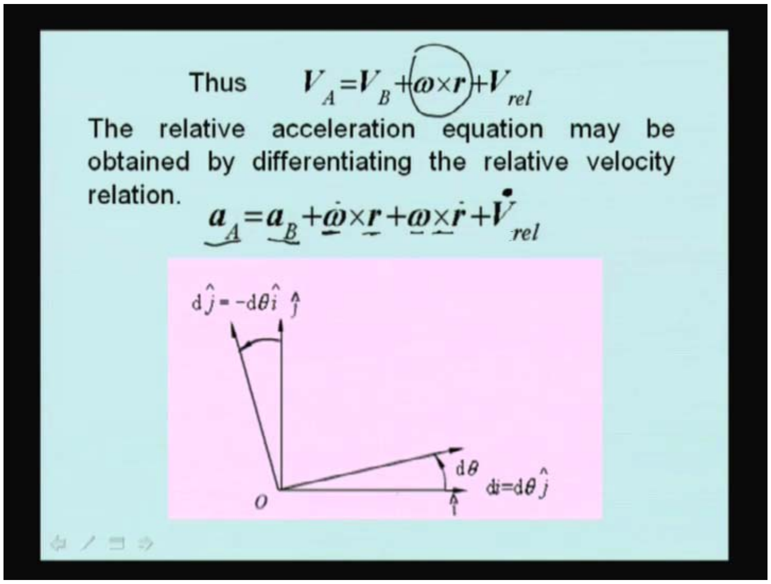

Another equation is this; velocity V_A is equal to V_B plus omega cross r plus V_{rel}.