Dynamics and Control of Mechanical Systems
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Lecture-19
Simulation Using Computer Tools

In this last lecture on dynamics we look at simulation of multi-body systems using computer tools.

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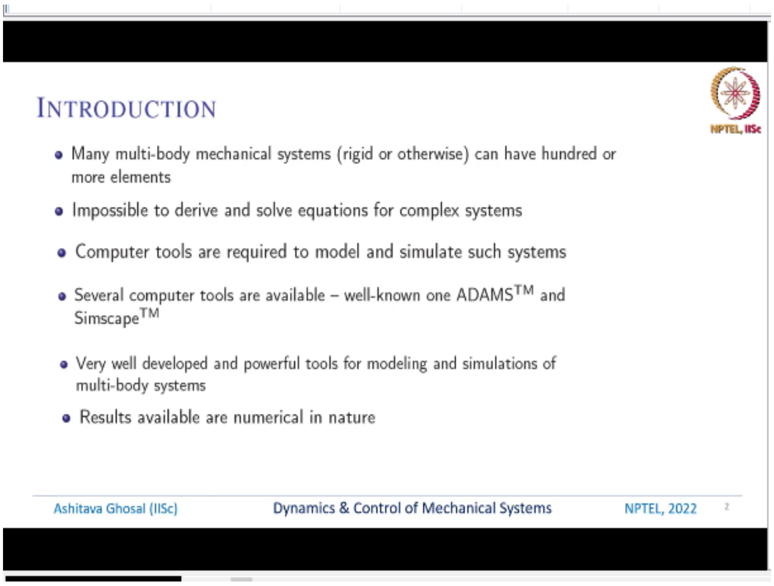

A brief introduction: Many multi-body mechanical systems rigid or otherwise can have hundred or more elements. It is physically impossible to derive and solve equations for complex systems such as these multi-body mechanical systems with many elements. So, computer tools are required to model and simulate such systems. There are several computer tools which are available.

The well-known one is ADAMS and also Simscape. Simscape is compatible with Matlab and there is a student version available for ADAMS and also for Simscape which these NPTELS students can use. These are very well developed and very powerful tools for modeling and simulation of multi-body systems. And we will go through these ADAMS and Simscapes very, very briefly.

The results are available but they are numerical in nature. So, you will not see equations of motion, you will not see terms like $m_1 r_1^2 + I_1 \ddot{\theta}_1$ things like that. Nevertheless you can still simulate these mechanical systems and get numbers, we can see how each joint or each link is moving.

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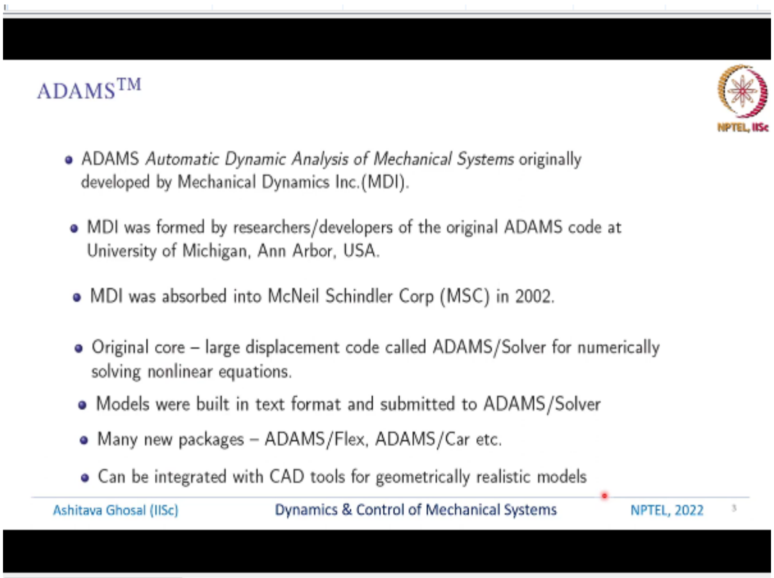

So, let us start with ADAMS. ADAMS is **a** stands for automatic dynamic analysis of mechanical systems. So, that is ADAMS, it was originally developed by mechanical dynamics incorporated MDI. This company MDI was formed by researchers and developers of the original ADAMS code at university of Michigan, Ann Arbor USA. The MDI was absorbed into another company called McNeil Schindler corporation or MSC in 2002.

The original core of ADAMS was basically a large displacement code called ADAM solver for numerically solving nonlinear equations. So, you could have large displacements. So, it is unlike a finite element code, in a finite element code the displacements are small. In this case you can have joints which can move by several degrees or rigid bodies which can move substantially.

So, it is a large displacement code called ADAM solver which was developed by these researchers at university of Michigan. The models were originally built in text format and submitted to this ADAM solver. Nowadays there are many new packages, there is something called ADAMS flex which is for flexible multi-body, you can also have ADAM'S car where you can model the car and make it move on a road with different kinds of surfaces and tires and so on.

The current ADAMS can also be integrated with CAD tools for geometrically realistic model. So, I can have the shape of a car or a wheel or some other mechanical object which is designed using CAD tools and then that geometry can be imported into ADAMS and then this whole mechanical system can be simulated.

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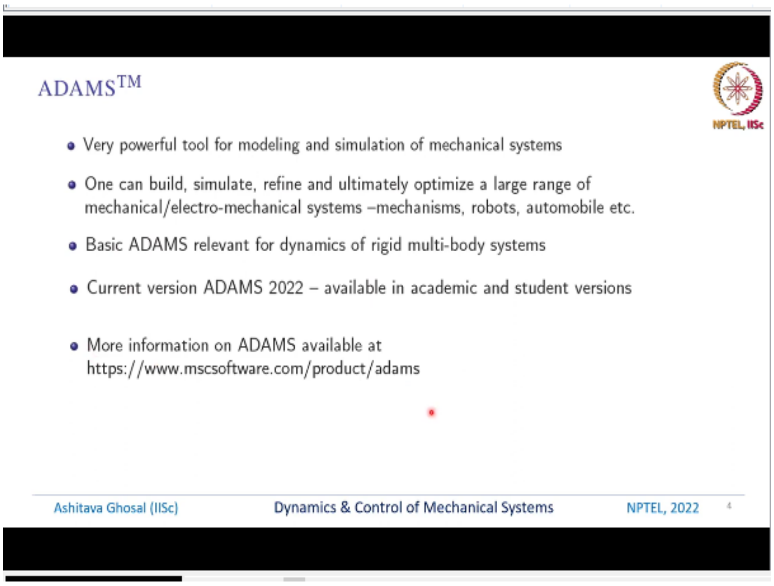

It is a very powerful tool for modeling and simulation of mechanical systems and in this lecture I will very, very briefly tell you what are some of the features are, one can build, simulate, refine and ultimately optimize a large range of mechanical and electromechanical systems; things like mechanisms, robots, automobiles etcetera. The basic ADAMS is what is relevant for dynamics and rigid body systems is what I will show you.

If anybody wants to learn more details about ADAMS then he has to spend some time on this code. The current version of ADAMS is 2022 and it is available in academic and student versions, the student versions you cannot build very, very big mechanical systems but nevertheless you can learn ADAMS. And student version is free as long as you write to the company and say that you are a regular student of such and such university or college they will let you use ADAMS for some length of time free.

The more information on ADAMS is available at this mscsoftware.com and you can go to this link and see ADAMS. MSC also makes lots of other software; ADAMS is only one of their products.

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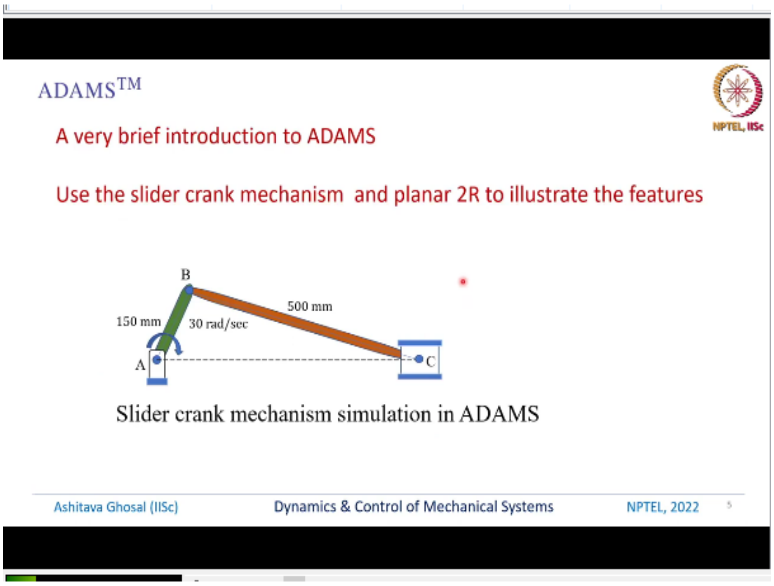

So, a very brief introduction to ADAMS, we will use this slider crank mechanism and the planar 2R to illustrate the features. That we will miss many of the features but nevertheless it will give you a flavour how we can model this slider crank mechanism or the planar 2R which we have discussed earlier and then simulate them. So, basically what is the slider crank mechanism? There is a crank, this link and this is connected to another link and then this is a prismatic joint.

So, this can slide along this direction. So, this is a model for a piston cylinder in a cylinder of a car. So, the piston goes up and down and it rotates a crank and then this rotary motion can be eventually transferred to the wheel. So, in this example we will assume that this length B to C is about 500, these 500 millimeters, this length is 150 millimeters and this crank can rotate by 30 radians per second.

So, what I want to show you is how we can model this slider crank mechanism in ADAMS starting from very basic steps and then I will show you what when you simulate this using ADAMS what does it do, what does it look like.

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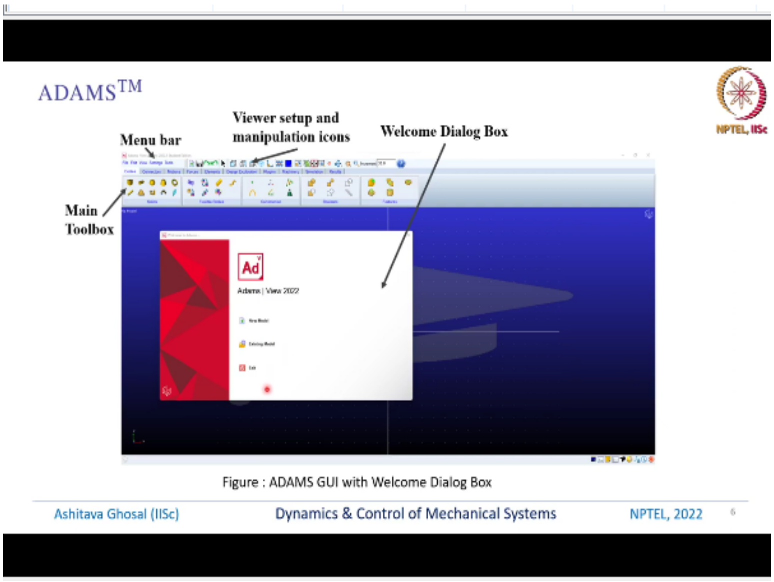

So, once you download ADAMS then you can see that there are these various places which says different things. So, first is this menu bar which standard windows menu bar your file, edit, view and so on. Then there is this tool box in which various kinds of solids, bodies then how do you connect them and then various features are available and you can click and drag and drop into this workspace.

And then there are this viewer, setup and manipulation icons and there is a welcome dialog box. So, you can click on a new model or you can load an existing model or you can exit.

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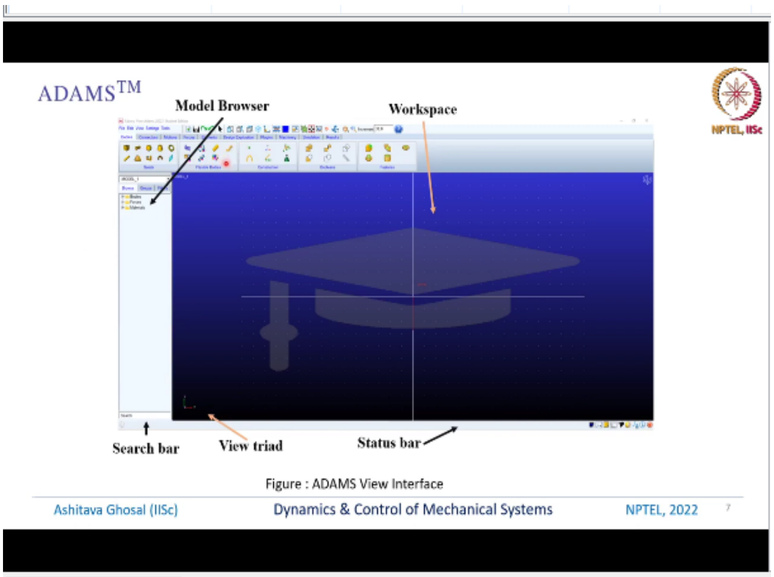

So, this is what the workspace of ADAMS looks like. So, there is some access x and y axis, there is a status bar, there is some triad which tells you it is not really visible but once you open ADAMS you will see that there is an x, y and z axis. And then there is a search bar and then on the left hand side you can see that there are bodies, forces and material, you can create your rigid bodies, you can apply forces and you can choose the material.

And this is the workspace and there are all these icons. I am not going to go into all the icons, but basically, we can select different kinds of solids, you can have a cylinder, you can have sphere and various other kinds of solids. We are not going into flexible bodies, but you can also have flexible bodies.

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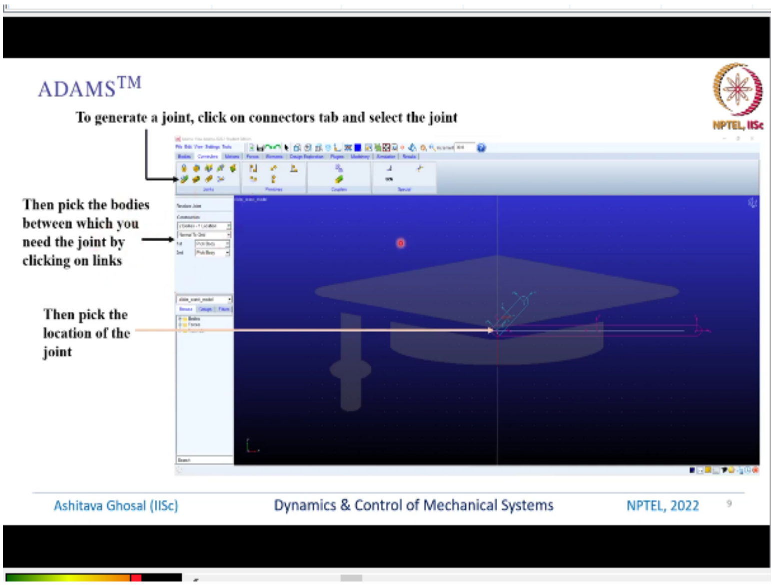

So, let us see how we can generate this slider crank mechanism. So, to generate a link we click on the bodies tab and select a link. So, we can select this link then define the dimensions of the link. So, you can see that this is of this length, width and depth. So, you can type in numbers. So, this is 15 centimeters and some 4 centimeters and some 2 centimeters.

Then you can place it here at the origin and you can give it the orientation. So, you can rotate it or make it look in a way we want and once you place it there are these local coordinates which are set up. These are coordinate systems which ADAMS internally uses. To make a joint, so, we have this link which is floating in here to make a joint you click on the connectors tab.

So, there is something which is called as connectors and selects the joint. So, in this case we have to select a rotary joint and then you have to pick the two bodies which is one let us say the fixed one body and then this crank and then you say that between these two bodies there is a rotary joint, you need to pick the location of the joint and you put it there. So, first select what kind of joint you want.

So, you have rotary, prismatic various other joints are available then you pick the two bodies which you need to connect using the joint and then pick the location of the joint.

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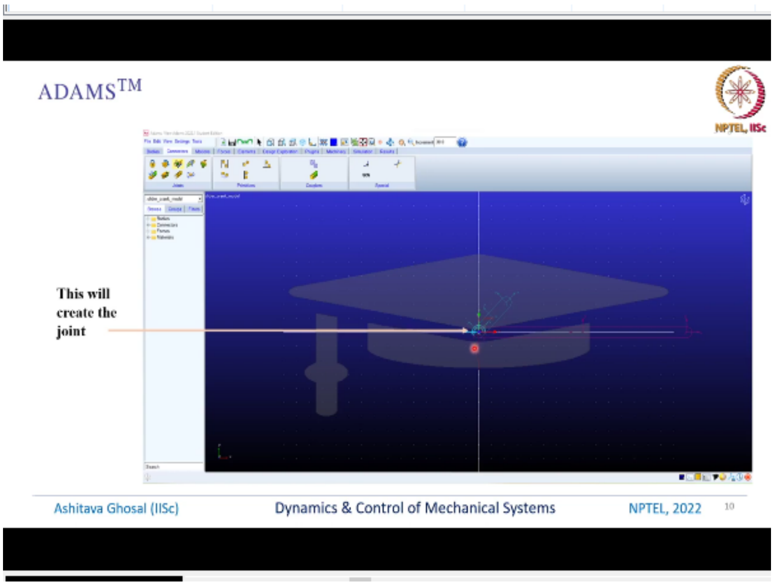

So, this will create the joint. So, this is a rotary joint and this arrow tells you that this is the direction of rotation. So, again anti-clockwise is positive.

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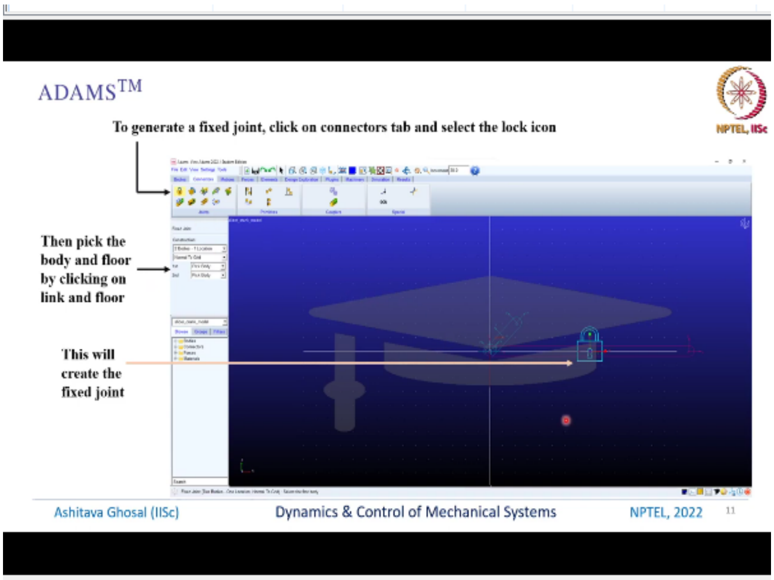

You also need to say which link is fixed. So, in your slider crank mechanism the base link is fixed. So, to generate a fixed joint click on the connectors tab and select the lock icon then pick the body and the floor by clicking on the link and floor. So, then this body and the floor is now fixed. So, this will create the fixed joint. So, in some sense very, very simple you drag and drop it needs a little bit of learning.

But most of the features are available in help you can also go and read the user manual and then it is reasonably easy. So, there are many demos which are available with ADAMS which you can try it out and then you can learn but I am showing you one such simple example of a slider crank mechanism.

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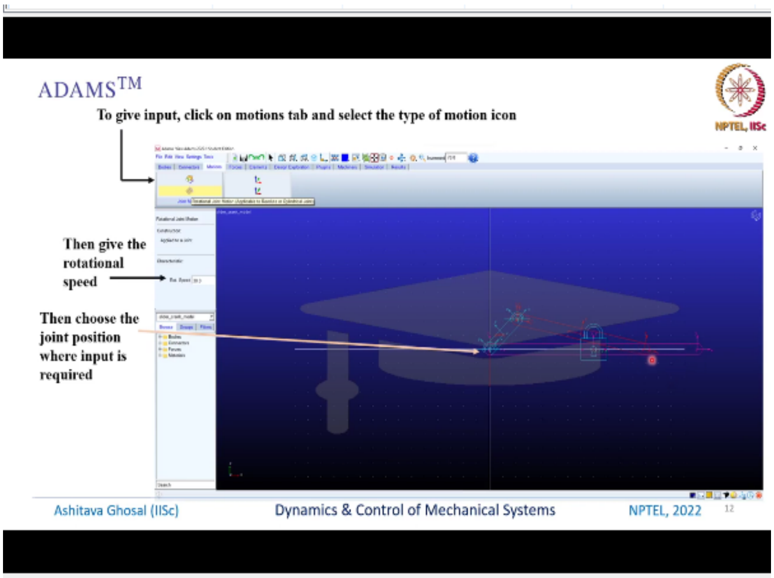

So, once you have this input link which is this and then you have another link and then this third link is the fixed then we need to give input, to give input we click on the motion tab and select the type of motion icon you want. So, if you want to give rotational speed then you can give the speed in this case we have chosen as 30. Then you choose the joint position where the input is required.

So, we want input here. So, what you can see is there is a crank, there is another one connecting link, there is a fixed link and then we have put one slider here.

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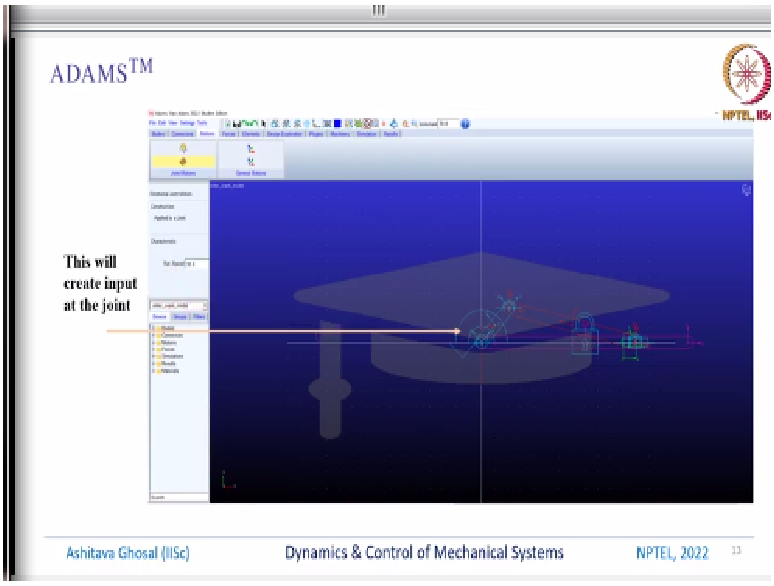

So, once you click on this and say that this is my input at this joint then you can see this is the speed. And as you can see there are many things which are also happening, so you can see that this is applied to this joint, the rotational speed is given and then there is a name for this slider crank model and so on.

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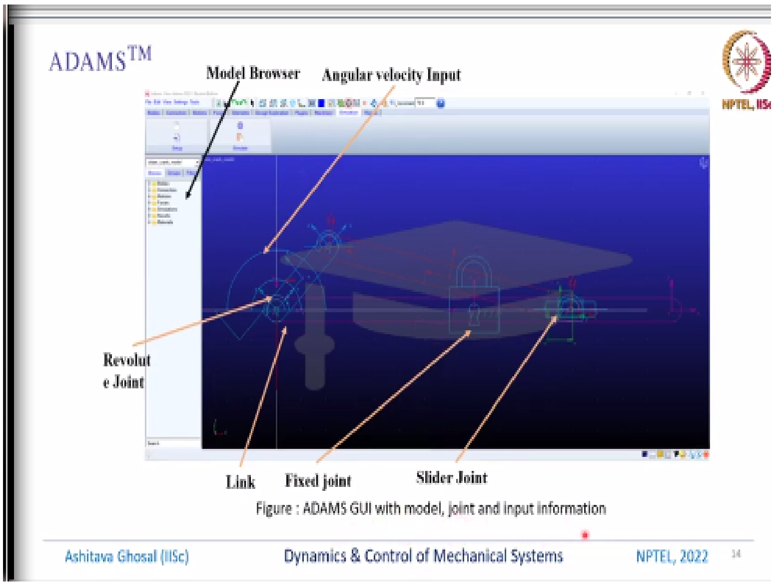

So, this is a student version, so there is some ghost pictures at the back but basically what we have done is we have created a revolute joint which is this then there is a crank, then there is another rod, connecting rod and then there is a slider joint. So, this is one link which is connected to the fixed ground then there is a slider joint and the top of the slider joint is connected to this place with another link and we are going to give a angular velocity input.

So, what all we have created you can see in this model browser here. So, we have bodies connectors motion and then now we can give some simulations and we can see results and then later on something to do with materials. So, final figure will be in this GUI which is a model of a joint and input information.

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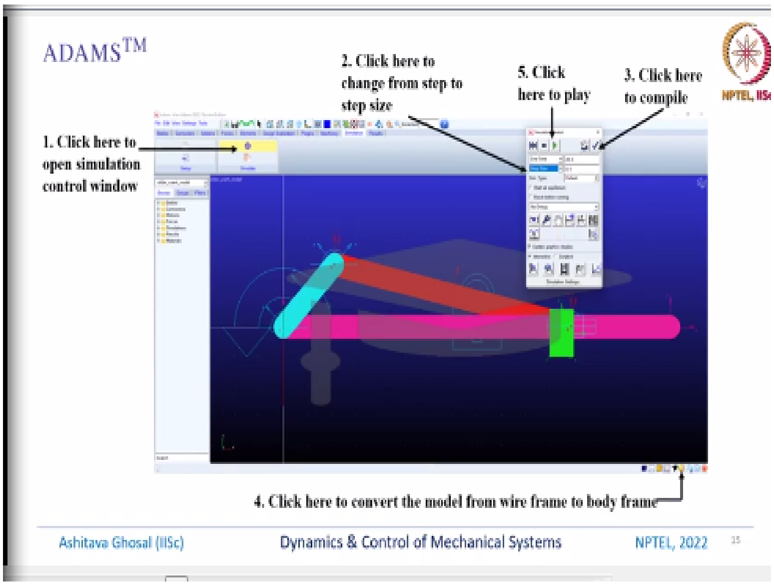

So, now that we have created this model, we want to do some simulations. So, if you want to do simulation we open this simulation control window which says simulate here. When you click this block like thing will appear and then you click here to change from step to step size. So, various clicks which you have to do to say that we want to now simulate this slider crank mechanism.

Once you have done all this, you can do this click this box to compile and if there are any errors or something like that it will tell you but otherwise you can now more or less ready to simulate. And this arrow here tells you that now you are ready to simulate and you can play this. There are also some features that you can convert from a wireframe model to a solid body in this frame.

So, you can see that this is one link, this is the input crank, this is the other one and this is the slider. There are many features in this dialog box, so I do not want to go into that, if anybody is interested you can try. So, you can give some initial time and some final time and then you can do step size. There are many defaults which are available, what integration routine you want to use and various other things are in this dialog box.

So, once you have done this you can simulate and here is a video. **(Video Starts: 17:00)** So, all the steps in this video are listed by the student TA who has done this. So, you input step size, you do end time and then it will do all this another dialog box will appear and then you can see that it is simulating. So, we are rotating this crank at 30 whatever rpm and I do not remember now it is 30 something and then you can see it moving.

So, this is a video of the slider crank mechanism step by step how to create a model of the slider crank then how to give the input then how to simulate it. **(Video Ends: 17:43)**

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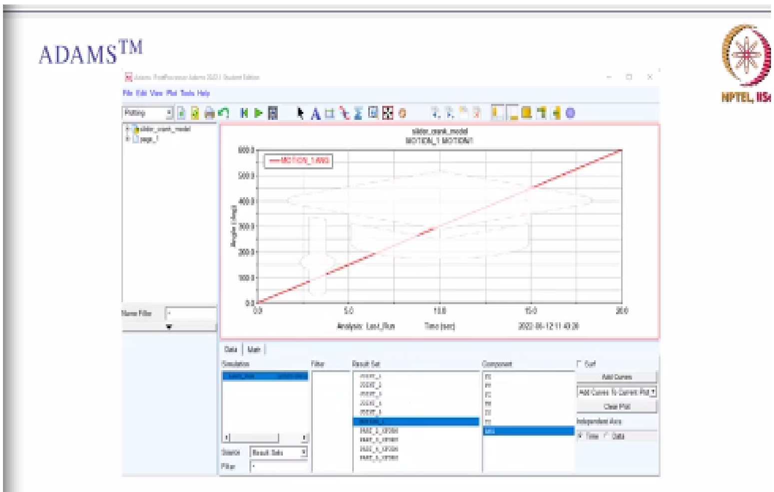

Figure : Theta vs time

We can also find out the plots of various components after the simulation. So, what you can see is that the angle is going from 0 to 600 because we are rotating at 30. So, in 20 seconds it went from 0 to 600, so it is 30 degrees per second, that is what was the input. And we can see all these things by going to this block here which tells you that this is motion, this is angle and you can add curves to plot here.

So, there are many plots which you can at the same place. So, the motion of the first joint is shown here, this is a straight line because we have given a uniform motion. So, this is a plot of theta versus time.

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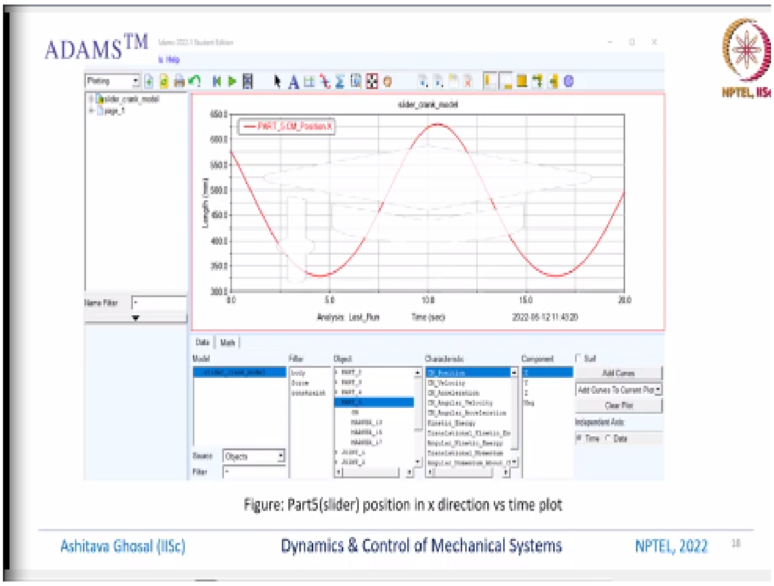

We can also plot the location of the slider; this slider is going back and forth. So, that is part number 5, it tells you that we have this slider crank model and this part number 5 is the slider part number 1 is something else, part number 2 is something else, I want to see the motion of this slider and we can see the position, you can also see what is the velocity, acceleration, kinetic energy various things.

And you pick whichever you want and you say you add curves to the current plot. So, we are plotting the position which looks like this. So, it makes sense, right, a slider crank mechanism will basically go forward and backward in some periodic manner.

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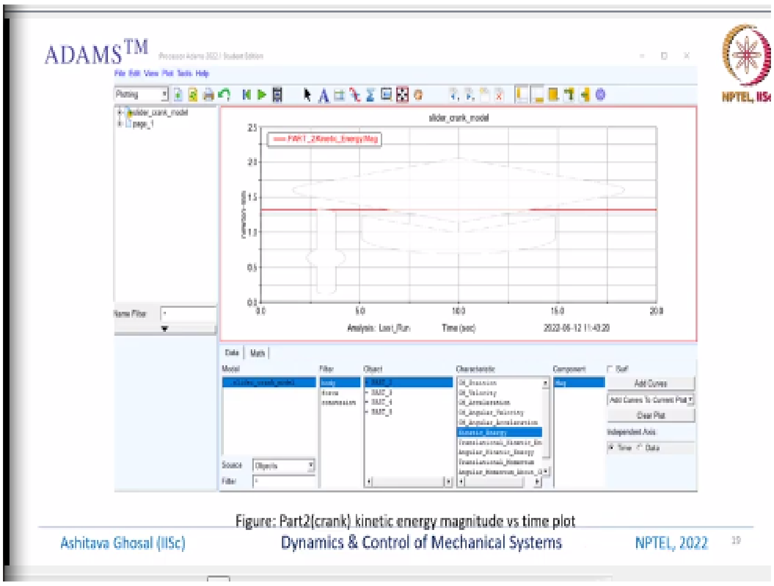

The kinetic energy of the system also we can plot, what is the kinetic energy? It is like $\frac{1}{2}mv^2 + \frac{1}{2} I\,\omega^2$ of all whichever part you want. You can either plot for part 2 which is in this case rotating or you can plot for the slider or you can do for various other bodies and again you add that curve to this plot and you can see. So, here omega is constant, so $I\,\omega^2$ will be constant and that is what is shown here. So, this figure is for part 2 which is the crank and this is a plot of kinetic energy versus time.

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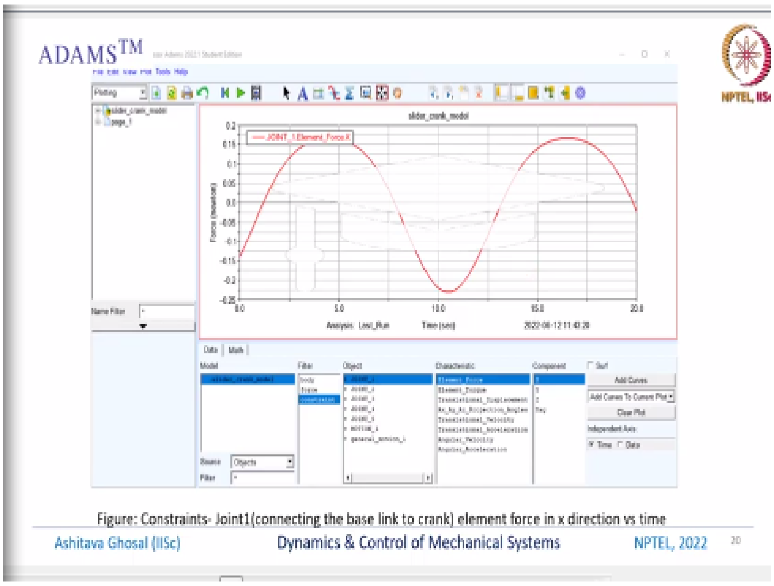

Figure: Constraints- Joint1(connecting the base link to crank) element force in x direction vs time

We can also check the constraints. So, remember this is a closed loop mechanism, this is a parallel configuration. So, hence at the joints there are some constraints, so there is a loop-closure constraint in this case also and we can find out what are the forces at each one of these joints which are the constraint forces. There is 1 torque which is making it move back and forth but at the second joint there are constraint forces.

So, I can plot the various constraint forces also. So, in this case for joint 1 we are plotting the F_X force, so joint 1 is a rotary joint. So, but there are some constraint forces in along the x direction maybe y direction and some other joints you will have some other constraints. So, I can find out these forces which are acting at the joint and this is very, very important and very, very useful to design that joint.

So, if I know this is the x component and the y component of the force which is acting at the joint then I can choose the bearing. Similarly I can find forces at other places, so I can design the link dimensions to withstand those forces. So, although the F_X *and* F_Y do not contribute to the motion, they are required for design.

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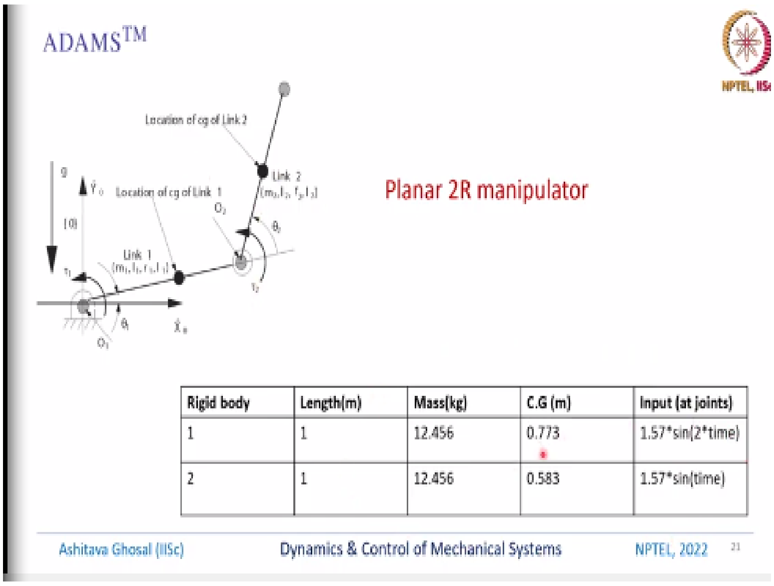

So, let us take another example which is this planar 2R manipulator and for this planar 2R manipulator we are choosing mass and length similar to what we did for the simulations using MATLAB and the CG is also similar. The input however is different, in this case the input at the joint is 1.57 into sin $sin\ (2\ *\ time)$, so it is sin $sin\ 2t$ and this is 1.57 into sin $sin\ t$, so this is like $\pi/2$.

This is just chosen arbitrarily we can choose some other inputs at the joint, so theta 1 will go in this form. So, this was the planar 2R robot, we have chosen these numbers.

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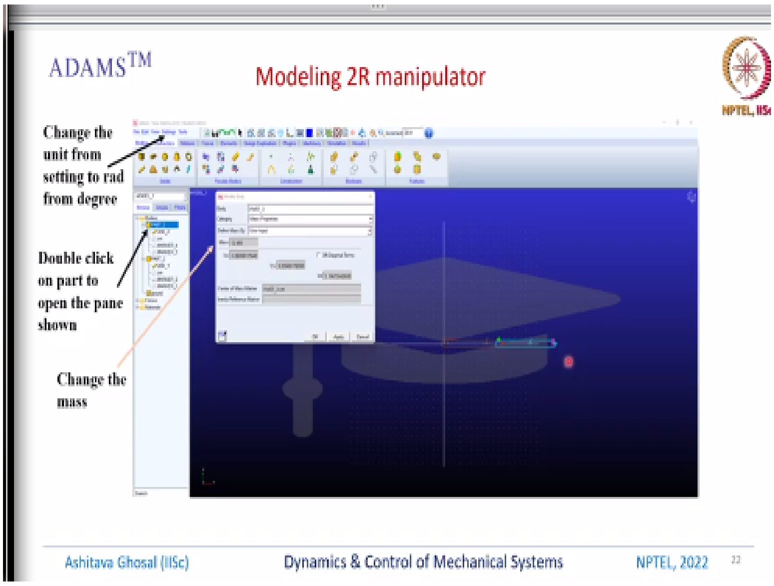

And again we can make a model of this 2R manipulator. So, we start from this we change the unit from setting to radians to degrees, you can do all this in the settings. Then you double click on the part to open the pane shown here then you can change the mass. Because now whatever you are modeling the mass is what you have specified, so you can specify the inertia, you can specify the mass.

If you choose a material and you give some length, width and dimension ADAMS will automatically calculate the mass and the inertia. But here I want the mass and inertia as specified by something else. So, we can change the mass, and this is the link.

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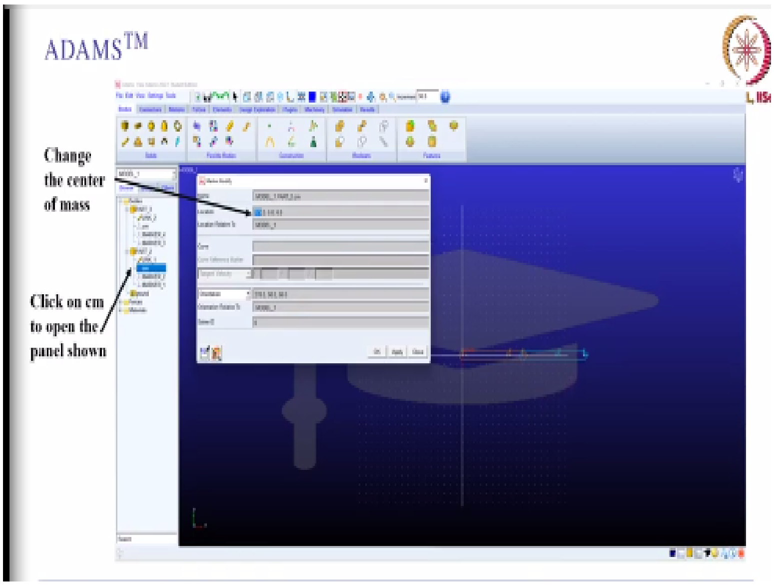

So, we can also change the center of mass and again we can click on this and open a module and there you can say that this is model 1 and these are the center of mass and you can type it and change the center of mass. So, this is now the link 2R robot, so if there are 2 of these and we can change the center of mass, the mass of each link and so on.

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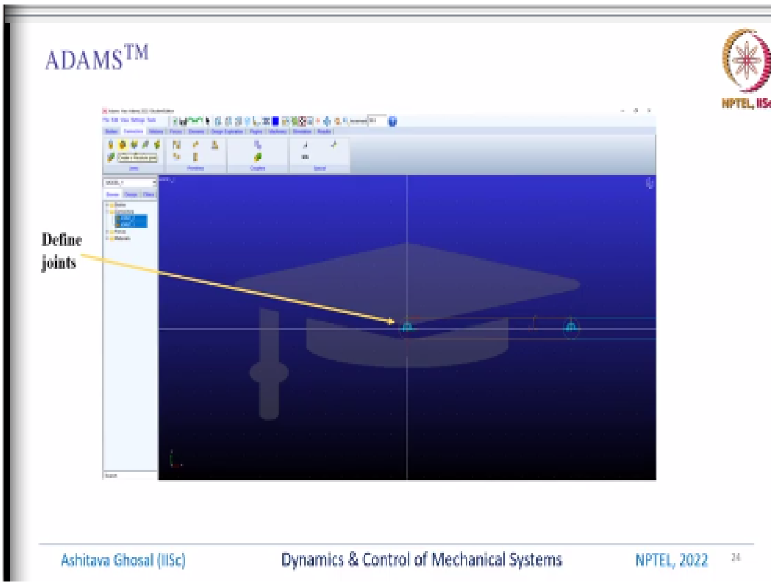

Then we need to put the joints. So, we define one rotary joint which is at the origin and another rotary joint which is a distance of 1 meter away because the lengths are 1 meter. So, we will pick rotary joints and put it here, very similar to what we did for the slider crank mechanism.

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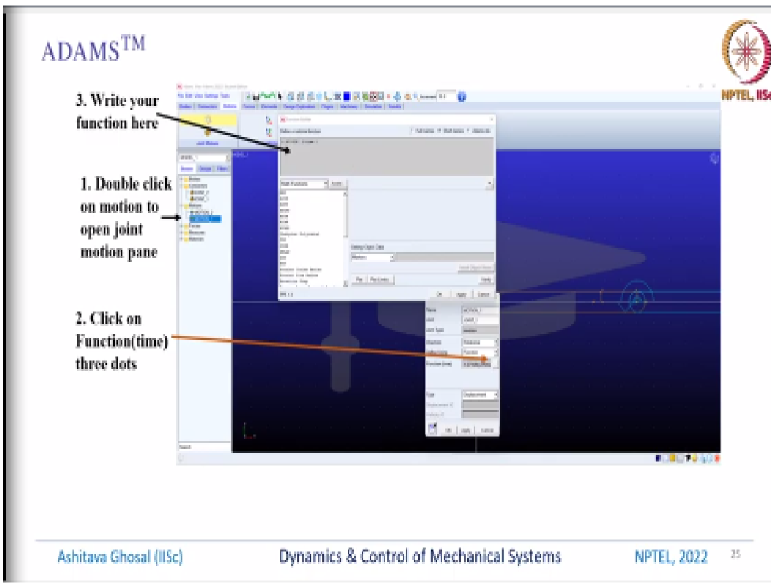

So, once you do all this you can double click on the motion icon here to open a joint motion pane. So, here what you can do is you can click on the function and give your own function. So, I want 1.57 into sin $sin\ 2t$ for the first joint, how do I do that? You open this and there is a function time and you can type it in, so we can write our own functions here. So, there are various ways of putting function, so sine and cosine they are understood by ADAMS.

But you can put some other functions also. So, there are some standard ways to input the motion which you want to put.

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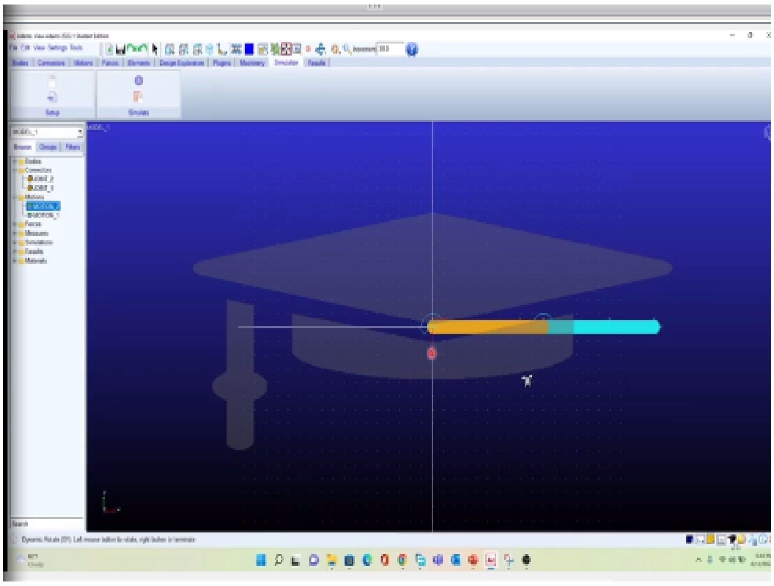

So, once you have done all these things then you can see whether we can simulate. So, this is the planar 2R robot but planar 2R system serial chain. So, I have 1 link here, 1 link here, there is 1 joint here, 1 joint here and I have given some specified motion. So, one of them is $1.57 \sin sin\ 2t$, another one is $1.57 \sin sin\ t$. **(Video Starts: 26:19)** And here is a video which says how you can simulate.

So, you can give some end time, some start time and then if it is everything is fine it will say successfully done and then you can see it moving, when you press that green arrow. So, it is reasonably simple of course you need to use it to learn a little bit but the learning curve is very small. **(Video Ends: 26:52)**

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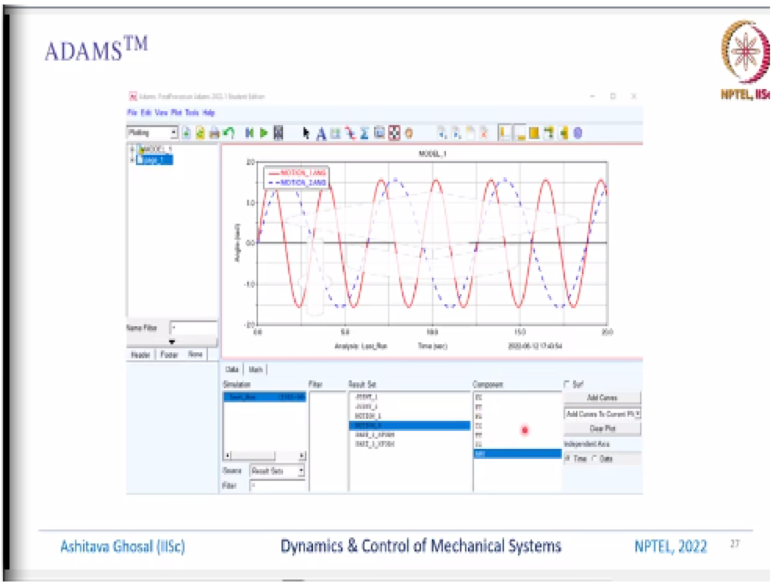

And then you can plot all these various angles. So, in this case I am plotting angle 1 and angle 2 and again you go here and you see that this is the last run we want motion, we want angle and we can plot these curves. As usual if you wanted we could have also obtained the constraint forces which are acting at the joints F_X, F_Y, F_Z and so on.

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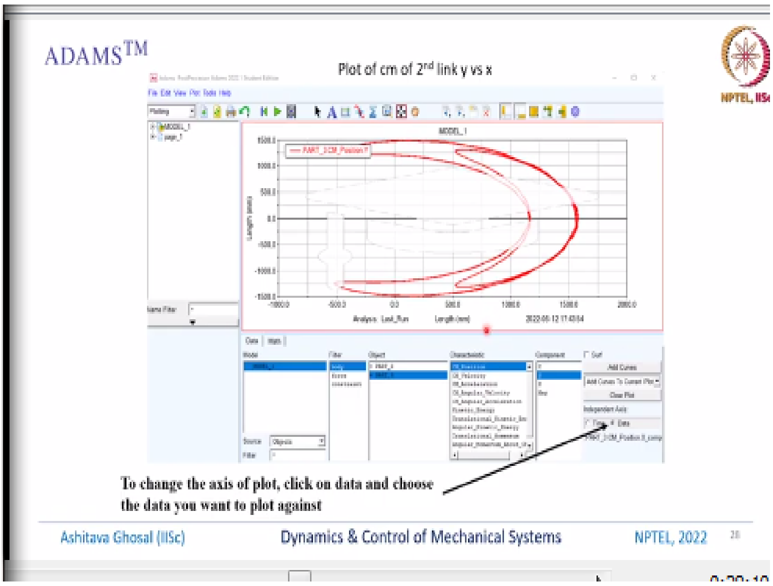

And you can also plot the motion of the tip. In this case the motion of the tip is in this plane, remember in the examples which we did it was in the x-y plane and it was moving vertically down, in this case it is different. We are giving some input to the joints and it is moving in the x-y plane and you can see what the tip is doing. You can also change the axis of the plot; you can click on the data and choose the data you want to plot against. So, we can plot here x versus y, everything need not be as a function of time.

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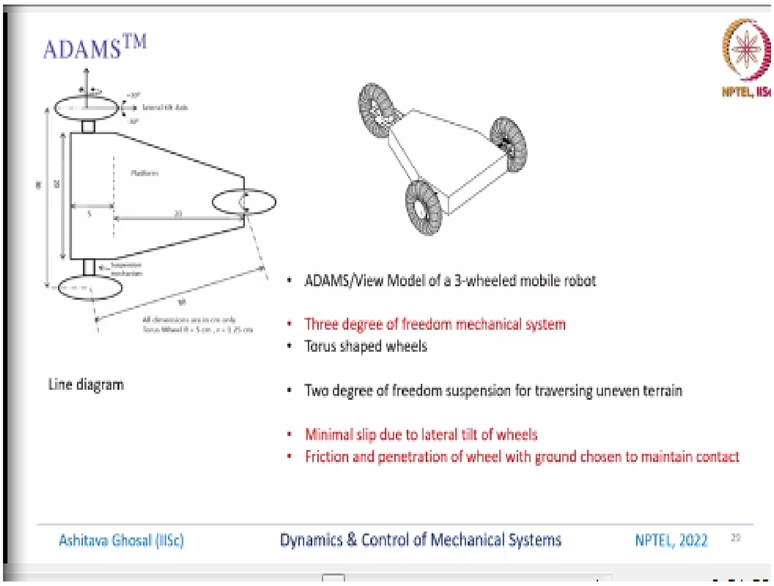

So, ADAMS is a very, very powerful tool to give you a flavour, there was a student of mine who did his PhD and we wanted to simulate the motion of this 3-wheeled mobile robot in ADAMS and this is what he did. So, the dimensions of this mobile robot are given like this that we have these 3 wheels, it is like auto but of course there are much more subtleties in it. The wheels themselves can rotate about one axis but it can also tilt, so this is not a normal wheel it is a torus shaped wheel.

And then this is the wheel which is mounted on some sort of a platform, the front wheel can be steered, the rear 2 wheels can be driven and the 2 wheels can tilt sideways. So, this is 30 degrees lateral tilt, this dimension is about 30, this is 20, this is 5 and all these dimensions are given. So, this is a line diagram and then you can make a model of this 3-wheeled mobile robot in CAD model and then you can import it.

So, this you can show is a 3 degree of freedom mechanical system, there are 3 inputs which are required, the 3 inputs are the rotation of the 2 rear wheels and the steering of the front wheel. These wheels are torus shaped because why? We wanted it to be tilting sideways, so there is a lateral tilt which is possible of $\pm 30\ degrees$. And in order to accommodate this lateral tilt and also go over uneven terrain you need a 2 degree of freedom suspension.

So, this thesis was on designing mobile robots which can traverse uneven terrain and then also tilt and without too much slip. So, if you allow these wheels to tilt you can show mathematically that there will be minimal slip; it will slip very little if you allow it to tilt.

And in ADAMS if you want this mobile robot to move over an uneven terrain you can make the uneven terrain in a CAD model, you can also make this mobile robot in a CAD model.

You can import both of them and to make sure that the wheels are always touching on the ground you need to fix something called friction between the wheel and the ground and also you need to ensure that these wheels are penetrating a little bit into the ground, that will ensure that these wheels are always touching. So, once you give these inputs to the wheel which is these rotations here and the steering here and then you make sure that the wheels are always on this uneven terrain then you can see how this mobile robot will move. **(Video Starts: 31:30)**

And here is a video of this mobile robot which is moving on this synthetically created uneven terrain and all these simulations are done in ADAMS. So, ADAMS is not for simple things like 2 degree of freedom, planar robot or a slider crank mechanism we can do very, very sophisticated and advanced 3D simulations. So, let us watch this, so he has given some inputs to these 2 wheels and some steering angles very similar to the 30 degree which we did for one of the links.

But now we have for all these 3 inputs and this mobile robot will go over this uneven terrain. So, more details are available in this paper which appeared in 2015. So, if you watch carefully you can see that these wheels are tilting and you can do these simulations and then you can capture this animation and you can make a video in ADAMS and then you can show such really nice simulations.

And you can look at this simulation from different angles as it is being done here. So, this ground is uneven and it has created separately in some CAD model. So, basically you can see that there is some unevenness in this direction is some oscillating this way and it is also oscillating in the other directions, so there are some hills and valleys in both directions. **(Video Ends: 33:34)**

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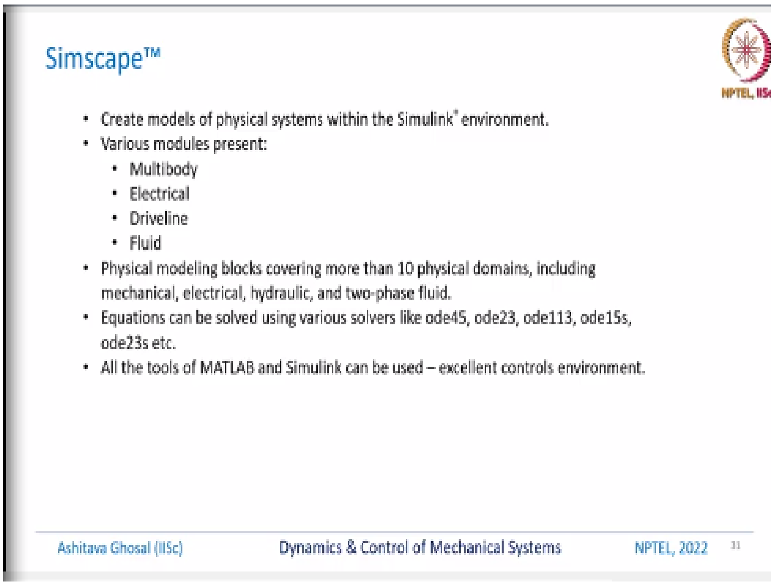

So, what I wanted to tell you is that this computer tools are very sophisticated, very powerful and you can do all kinds of simulations you can do really, really complex multi-body systems and you can simulate them. One more this simulation tool is Simscape; this is compatible with MATLAB. You create models of physical systems within the Simulink environment. So, Simulink is a tool box in MATLAB where you can make model and you can simulate and you can also design controllers for this in Simulink environment.

So, again the student would have created one tutorial on MATLAB where some of these things would be mentioned. If you want to go deep, you need to go and look at MATLAB books or demos and help files. So, there are various modules which are present in this Simscape, you can have multi-body, you can have electrical, you can have drive line, you can have fluid.

You can have physical modeling blocks covering more than 10 physical domains including mechanical, electrical, hydraulic and 2 phase fluids the equations can be solved using various solvers ODE45, ODE 23, ODE113, ODE15S this is a stiff-solver, ODE23S is also another stiff-solver. You can pick which solver you want to solve your particular model and all the tools of MATLAB and Simulink can be used.

So, you can design controllers, you can use later on in this course we look at controls. So, you can use various control system design and modeling techniques inside Simscape. Because MATLAB and Simulink and Simscape are all integrated together.

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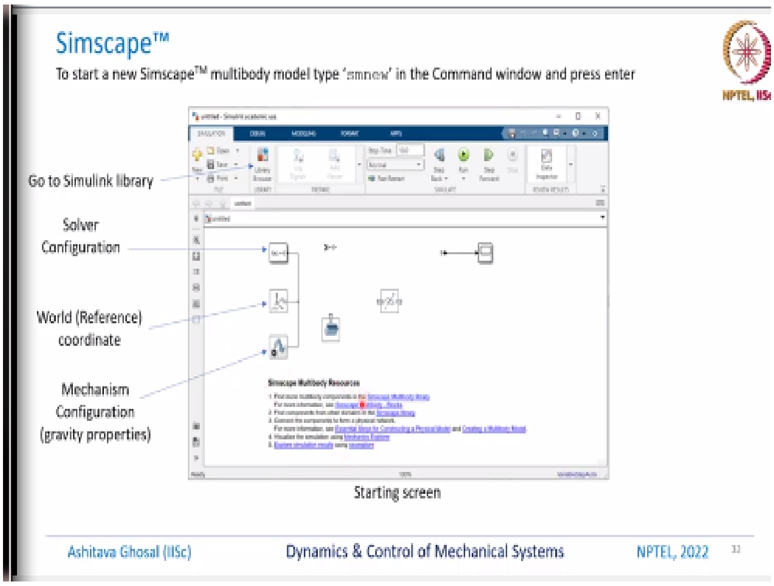

So, here is how it starts. So, to start Simscape multi-body model you type "smnew" in the command window and press enter. So, you have a command window in MATLAB, you type this and you enter, you can go to a Simulink library, you can also find some solver configuration and then you can also choose a reference coordinate system and then you can choose the gravity properties, mechanism configuration and so on.

And it is very similar to Simulink, so you can have blocks and you can have inputs and you can have outputs. So, we will not go into depth of Simulink but those of you who are interested can go and see Simulink and then Simscape multi-body resources. So, there are many help files which are available for Simscape.

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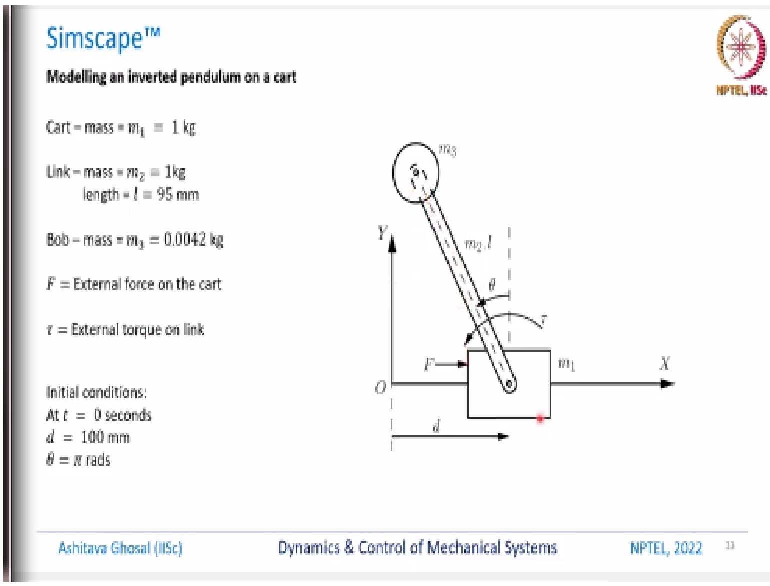

So, in Simscape we will take this example of a modeling of an inverted pendulum on a cart. So, this is a very classical problem in multi-body dynamics and control. So, basically what you have is a cart, so it is like a cart with wheels, it can go along the X direction and then on top of that there is a pendulum. So, the mass of the cart is 1 kg, the link length is 95 millimeters which is chosen the link mass is 1 kg and the mass of the bob is very small, it has been chosen arbitrarily.

So, what happens is when you move this body you need to apply some force and you can also apply a torque. So, instead of a 2R chain we have what is called as a PR chain. So, first joint or a first body is sliding and the second body is rotating. So, I want to see the motion of this pendulum on a cart, this is a very classical problem in controls and we will give some initial conditions, we will say that t at t = 0, this distance d the center of this cart is at 100 mm and this theta is π radians.

And we want to give some force and some external torque and then see what this pendulum and what this cart is doing.

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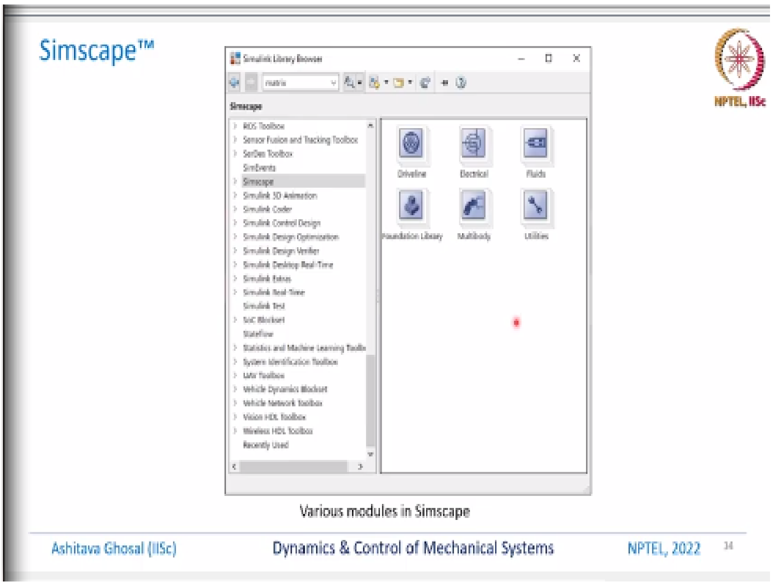

So, how do we do that? You go and click on Simscape and this has all these various modules in Simscape, you have drive line, electrical, fluids, we will not look into fluid and electrical.

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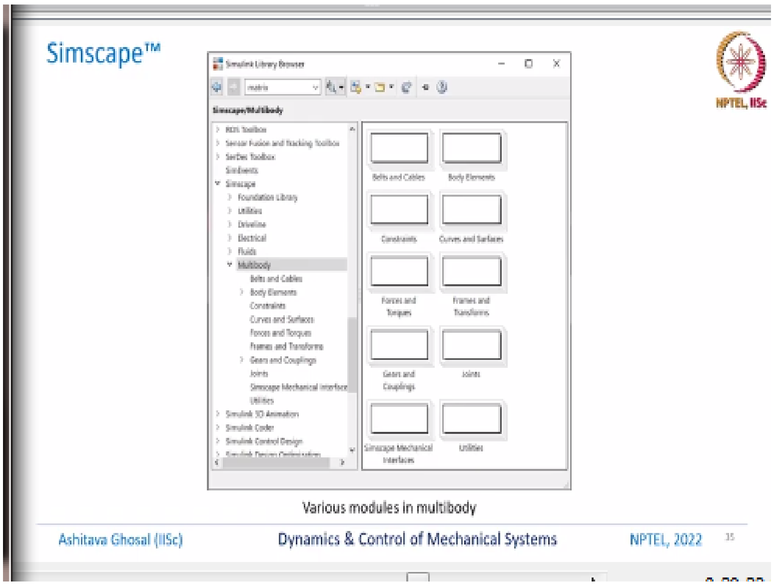

So, you choose multi-body and inside multi-bodies again you have all these bodies and how to connect them. So, we have body elements, you have belts and cables, you have forces and torques, you have joints and you have various gears and couplings and so on. So, you can click on each one of this and make a model of this cart and pendulum.

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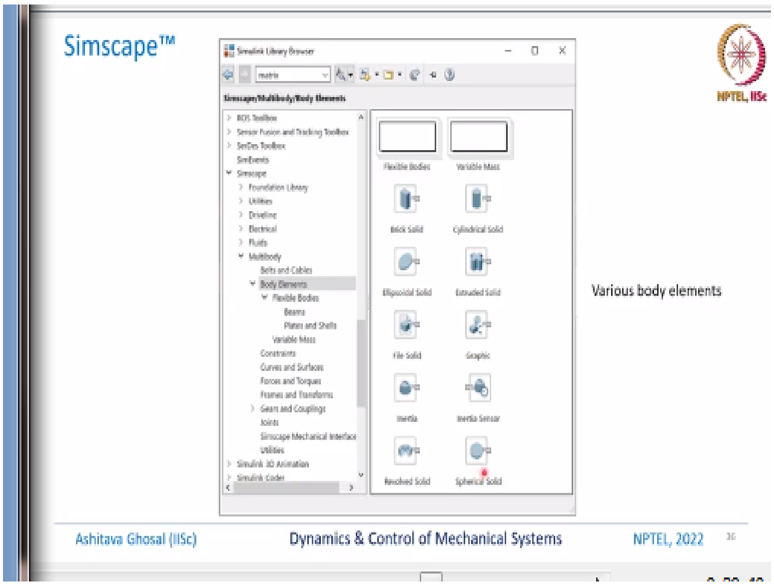

So, we choose this various body elements we can have a solid, we can have a cylindrical solid and various shapes are possible. And then we can have sensor, inertia, revolved solid, spherical solid various possibilities are there, so we can pick the various body elements.

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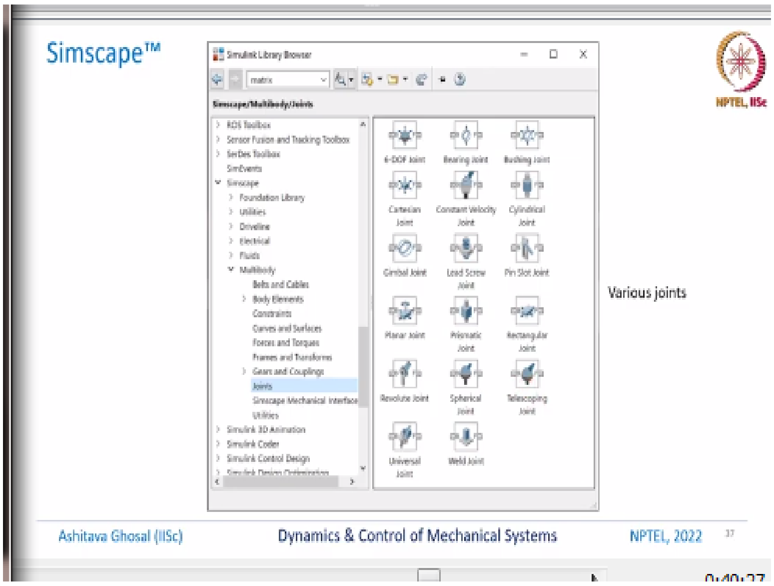

And then we have joints, we have 6 degrees of freedom joint, you have a bearing joint, you have a Cartesian joint, Cartesian joint basically allows X-Y-Z motion. Then you have planar joint, prismatic joint, revolute joint, prismatic and revolute we know, so you can go and click and you can pick these joints. So, we have looked at universal joint, weld joint is nothing but 2 rigid bodies connected together, so there is no relative motion. Telescopic joint is something like which one you can translate and also rotate about this.

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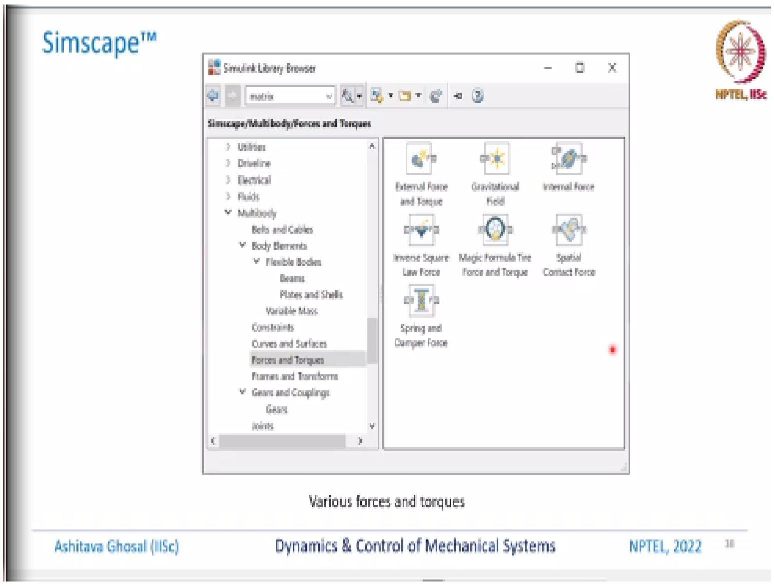

So, once you have chosen these bodies you can now select various forces and torques, you can have an external force, you can have gravity, you can have internal forces and then you can have various springs and dampers and various contact forces.

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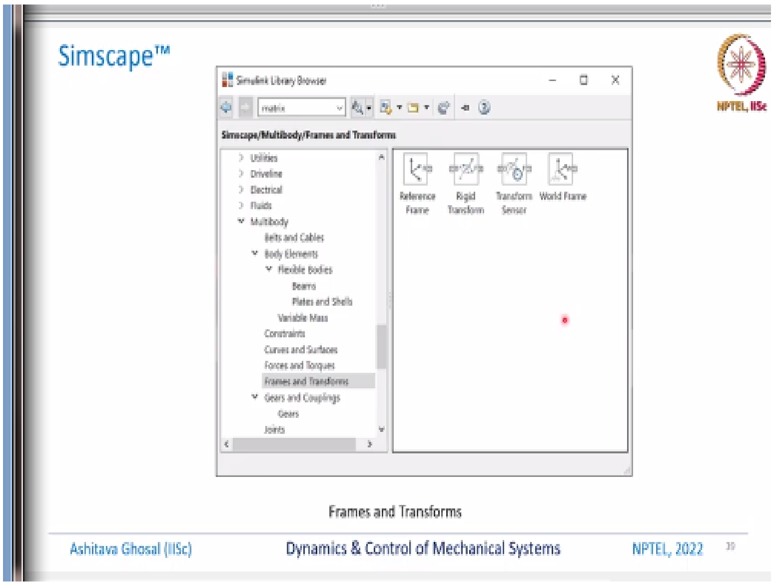

Then you can choose the reference frames. We can find out what is the fixed reference and then we have all these reference frames attached to different bodies.

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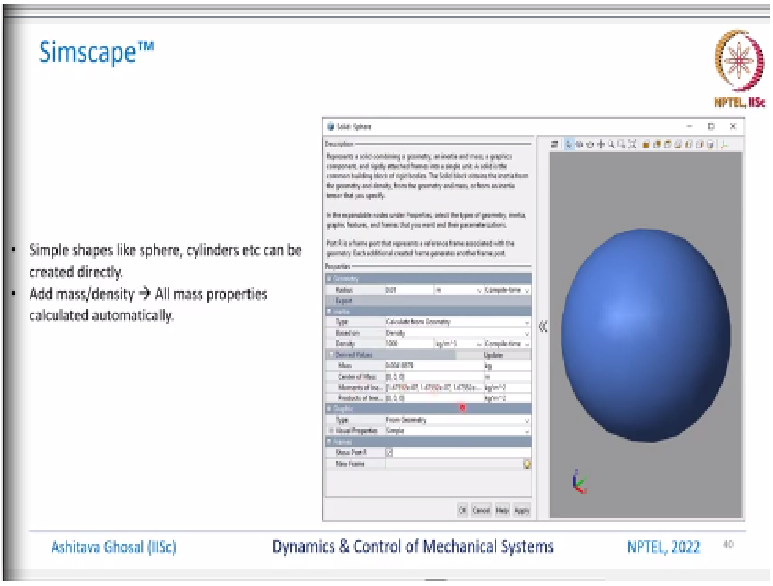

So, once you do that let us pick simple shapes like a sphere, cylinder and we can also create them if you want, you can add mass, density, all mass properties calculated automatically. So, if you make a sphere and then you say this is the density, everything will be calculated, what is the mass, what is the center of mass and various other things will be calculated.

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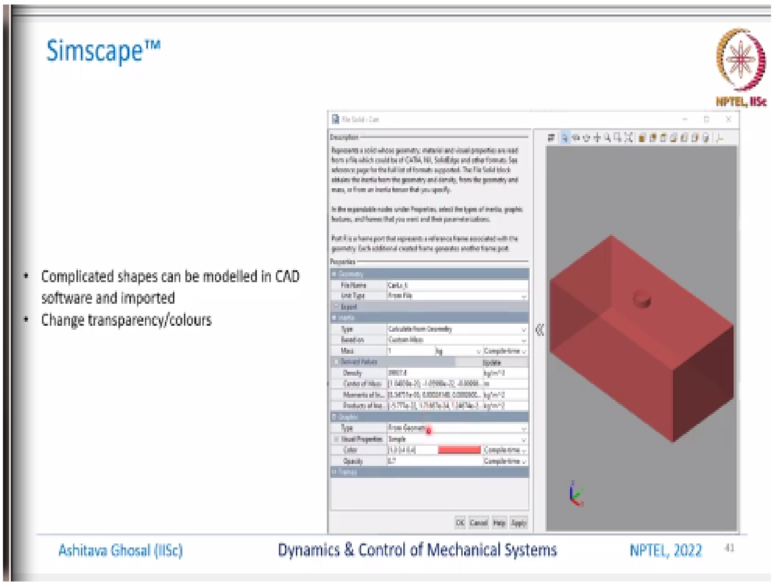

We can also make complicated shapes in a CAD system and import them. So, for example we can have a block with some small protrusion here. And again once you tell them that these are the dimensions this is the density it will find center of mass and various other things, inertia is also there.

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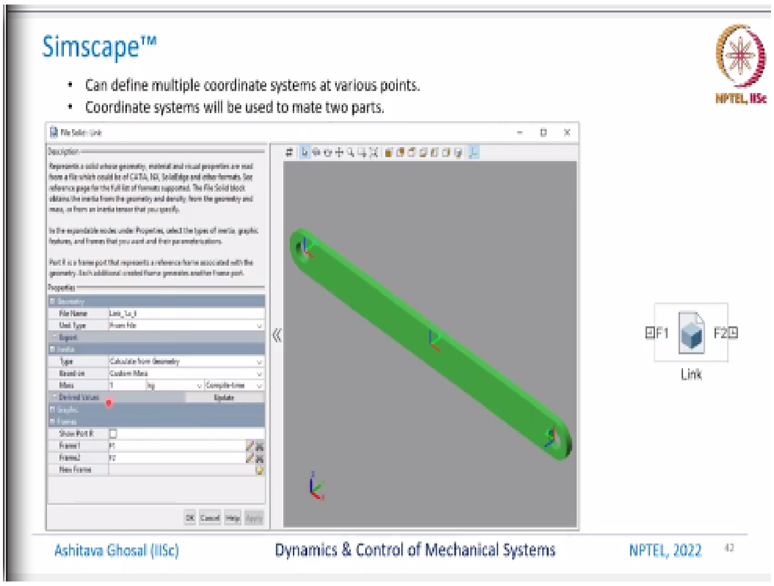

So, we can define multiple coordinate systems at various points. The coordinate systems will be used to meet 2 parts. So, in this case there is a link and there is a hole here and there is another hole here and there is a coordinate system at the middle and there are these coordinate systems in these 2 holes and we can have some way to say which link it is. So, this is $link\_1xt$ and you are saying from where you have got, you can calculate the geometry, you can customize the mass, you can do various things.

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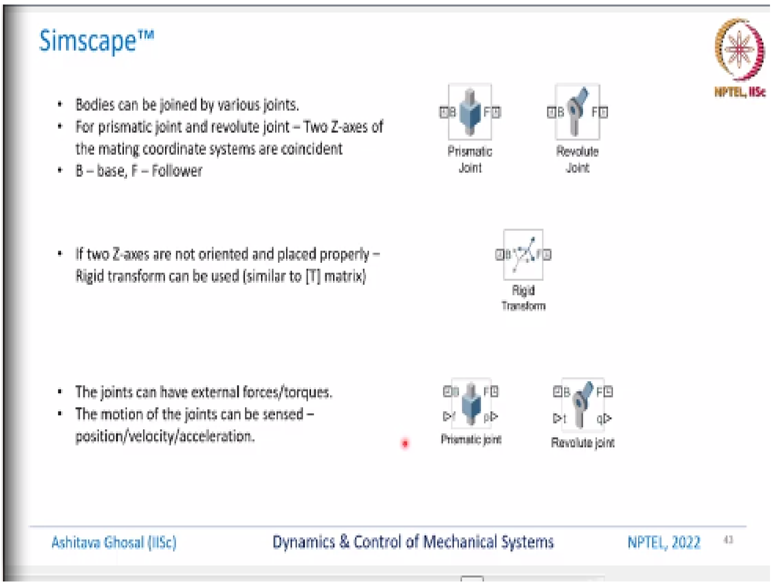

So, we pick bodies and they can be joined by various joints. For prismatic joint and revolute joints 2 Z-axes of the mating coordinate systems are coincident. So, we have one rigid body here and we have another rigid body inside and the Z axis of both these 2 rigid bodies are coincident. Same thing with the revolute joint and this is we have discussed earlier most of the time the Z-axis is the joint axis and that is what it means here.

That I have one body and this is another body and they are connected by a rotary joint which basically means that we have to make sure that the Z-axis of both of these at this point are coincident. So, if the 2 Z-axes are not oriented properly or placed properly you can use rigid transforms similar to the T matrix. So, you can do translation and orientation of these 2 rigid bodies such that you can put a joint there.

And you can also give external forces at the joints and torques at the joints and the motion of the joints can be also sensed by means of sensing we mean that you can find the position, velocity and acceleration at the joints.

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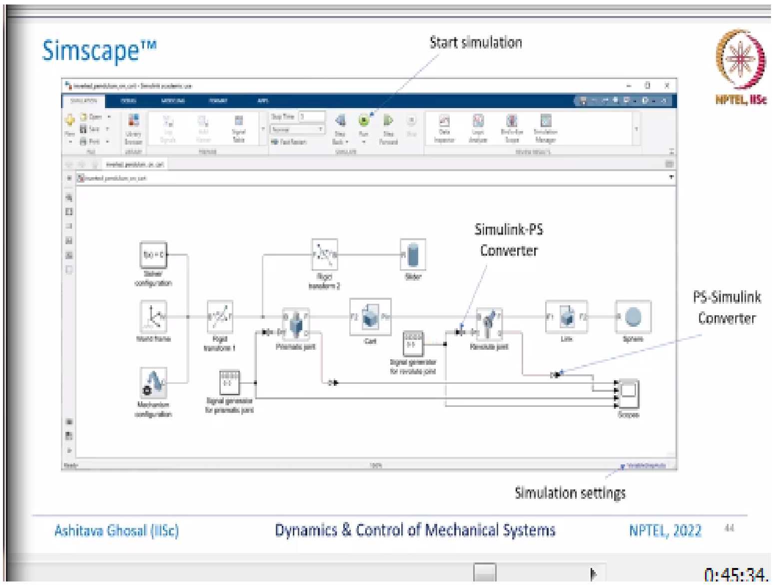

So, once you do all this then you can make a model and in the model you have some kind of a solver configuration. We have this reference coordinate system, then we have this mechanism configuration and this is rigid transform then you can give an input. For the input for the prismatic joint is some oscillation, then we have the cart. So, this kind of block diagram is very, very similar to what we do in Simulink or what we do in control system analysis and design using Simulink.

We will look at this in the rest half of the course little bit, not fully. So, we can have a link, we can have a sphere, the sphere is that mass, this link is that link at the end of it which is a sphere, then there is a revolute joint and then we have input to the revolute joint, then we have a cart. So, we can have all these various components and we can connect all these various components to show how motion or how each of them are connected.

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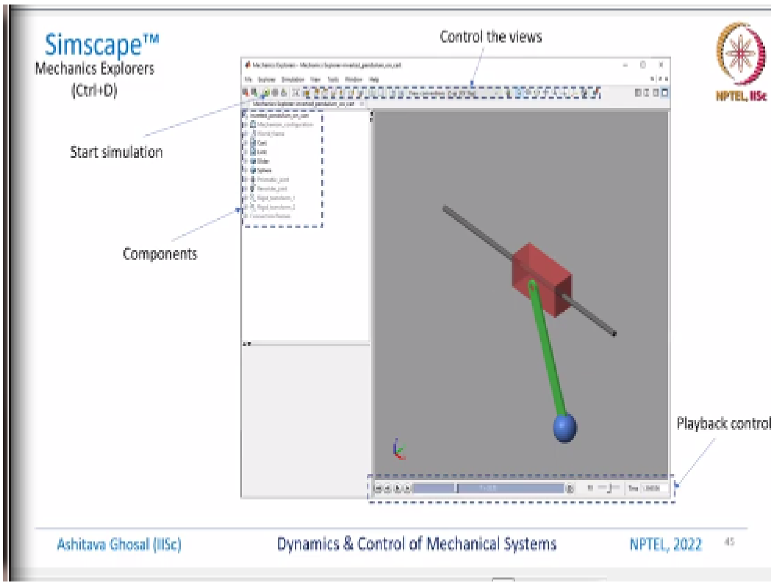

So, once we have connected all these things we can do simulation and inside the simulation you have various components. You can see that we have a cart which is actually this in this case then we have this link, then we have this slider that is between this and this there is a sliding joint and this is a sphere. And then we can see all these various control the views how we can move and then you can simulate.

So, this arrow tells you to start the simulation and here there is something called playback control, you can see at what time, what is happening and so on. So, we are quickly going through this, not to teach you Simscape or even the purpose of this is not to teach you ADAMS or Simscape but to give you a flavour that there are these modern simulation tools which you can use to find the motion of various components.

As you can see we have not yet talked about what is the equation of motion, we have not derived the equations of motion using Lagrangian or any other formulation. We have just simply made the model and then we are going to ask to simulate. And internally clearly there is some lot of work is going on to derive the equation of motion and then do simulation. But which is not necessary for you to know, we can just make the model and do simulations.

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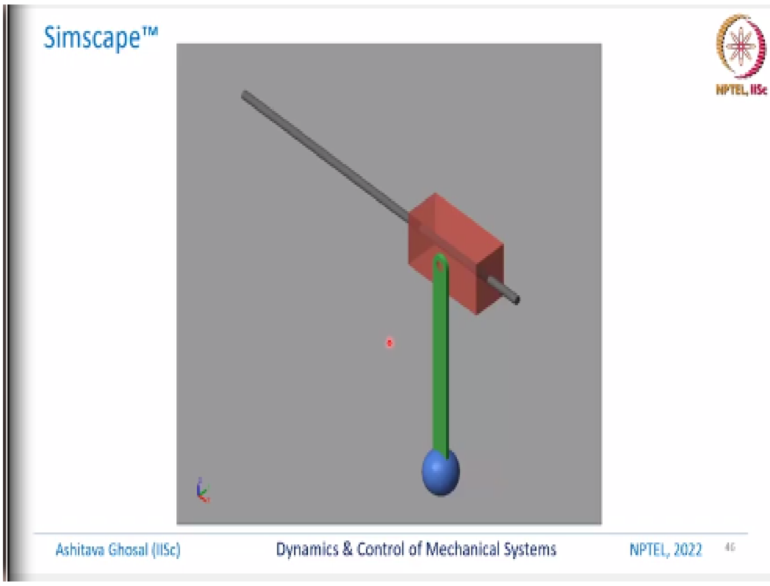

So, here is the model of the cart with the pendulum. **(Video Starts: 47:22)** And then you can see that while it is moving this way and that way, this pendulum will also oscillate. So, this is a very short simulation how do you know that this is correct that this is reasonable? The answer is people have worked on it for a long time they have tested, maybe they have even verified with experiments.

That the results which you obtained from Simscape and also from ADAMS they make sense. Because inside there is some way to generate equations of motion, constraints and then they are being solved. **(Video Ends: 48:05)**

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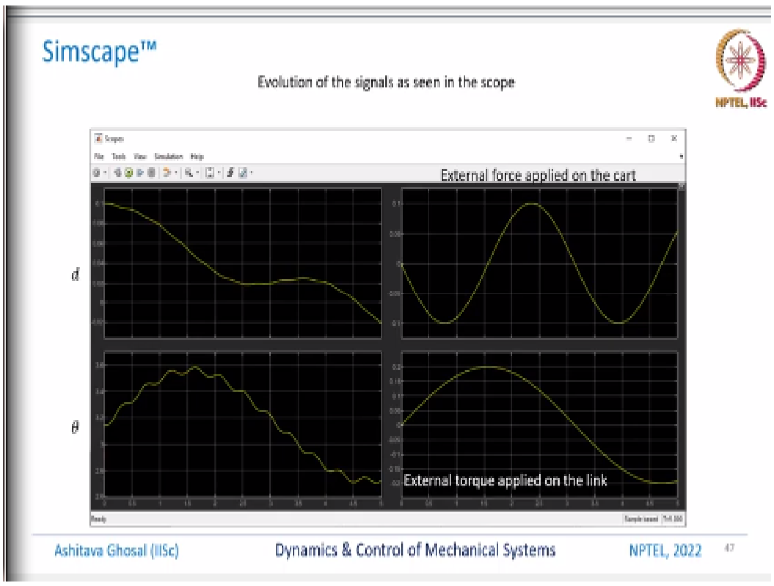

We can also plot the thetas and the d. So, this is the plot of theta as a function of time, this is a plot of d as a function of time, this is the plot of the external force, remember there was a force which was applied on the cart and then there is a plot of torque. So, for given these input this is how thetas and d will move.

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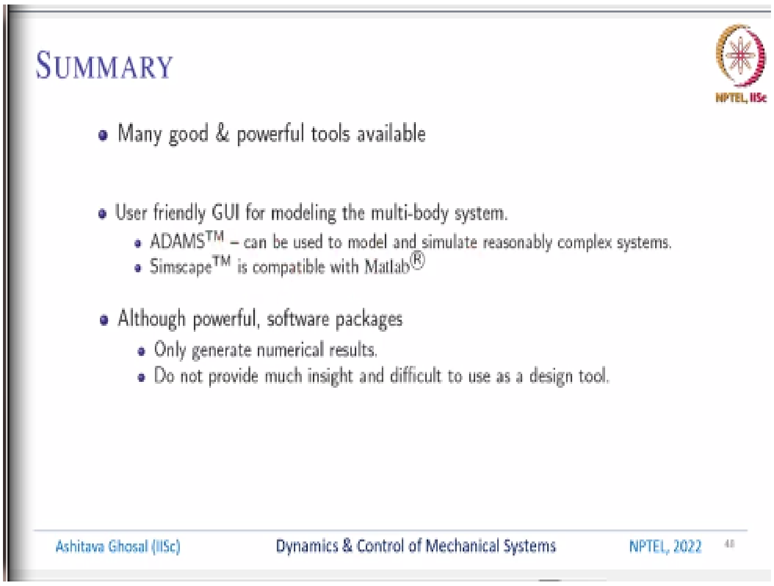

So, in summary there are very many good and powerful tools which are available for modeling and simulation. They have very user friendly GUI's graphic user interface for modeling the multi-body system. ADAMS can be used to model and simulate reasonably complex systems. So, there is a package called ADAMS car in which you can model most of the car, reasonably well and then you can show how the car will move on a road, how it will accelerate, how it will go on a slope and things like that.

Simscape is not as powerful as ADAMS but it is still reasonably powerful, one of the advantage of Simscape is it is compatible with MATLAB. So, there are lots of tools available in MATLAB for simulation, control system design and other things which you can use with Simscape. So, although these are very, very powerful packages, you should keep in mind that they generate numerical results, they generate nice videos they generate nice animation.

But basically you will find only numerical results, you do not see the equations of motion and you cannot say this term is important in this equation of motion, things like that to get good insight into this multi-body system and what is exactly happening it is not so easy. They do not provide much insight and it is sort of difficult to use as a design tool. So, you can run many simulations and get an idea as to how the system is behaving when you change some parameters.

But it is not in my view looking at the equations of motion of some systems and say that okay this term means this, this term means this, I can see what is the effect of the term on the coriolis acceleration or on the centripetal acceleration, when I change this mass what is happening. So, it is much, more easier if you have equations of motion and of course but many often or many times you do not have the equations of motion. So, then you have to fall back on these simulation tools.

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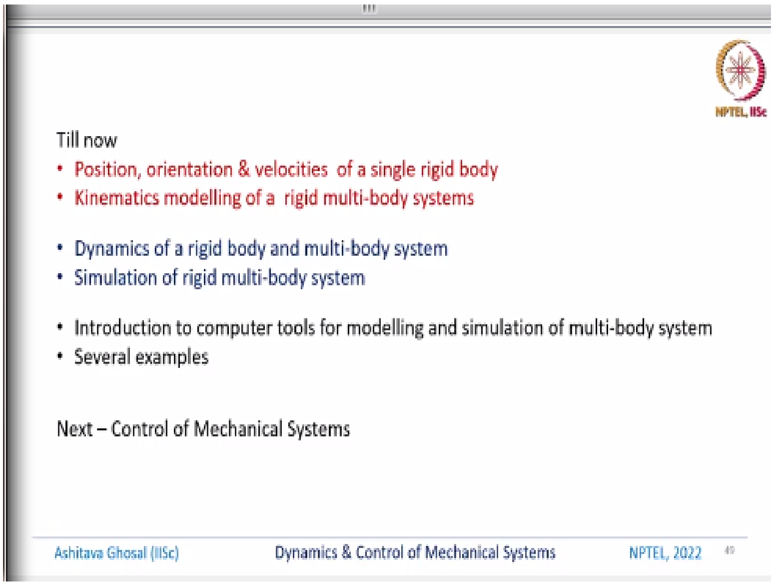

So, till now we have looked at position, orientation and velocities of single rigid bodies. We have looked at kinematics modeling of rigid multi-body systems then we have looked at dynamics of rigid body and multi-body system. We have looked at various ways of simulation of rigid multi-body system. I have also given you some introduction to computer tools for modeling and simulation of multi-body systems.

And we have looked at many examples, some are simple examples but somewhat like 4-bar mechanism, a rolling disk, a cart and a pole, a cart and a pendulum or even a spinning top. So, we have looked at many mechanical systems and we have derived equations of motion and we have simulated many of these equations of motion. In fact one of the thing is we looked at various ways of obtaining equations of motion.

We looked at basic mechanics which is Newton's law and Euler's equation, then we looked at this algorithmic Newton-Euler formulation, then we looked at Lagrangian formulation. And I showed you at least for one example all of them gives the same equations of motion. So, I have tried to show you this kinematics and dynamics of rigid bodies and rigid multi-body systems. In the next part of these NPTEL lectures we look at control of mechanical systems.