Principles of Engineering System Design

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Lecture - 28
Bond Graph Modelling of Dynamic systems

Dear friends, today we will discuss about the Bond Graph Method of System Modeling. In the last class, briefly explained the bond graph methods what is the importance of this method and how this method can be used for modeling of dynamic systems. Today, we will go in to the details of the modeling techniques; what are the important elements in bond graph and how do we develop a bond graph model for a dynamic system and then how can it be used for simulating the dynamic behavior.

So, as I explained in the previous few lectures we need to model the behavior of systems under various stages of design in order to understand the behavior of the system how we responds to particular inputs what kind of controls need to be incorporated and what kind of tuning is to be provided. In order to get a decide the outputs we need to use the modeling methods and bond graph is one of the methods which can be easily implemented for system design as I explained earlier, bond graph method is basically used for multidisciplinary systems where you have multiple domains like mechanical systems electronic systems electrical systems software computers and hydraulic systems.

So, when we have a system with multiple domains or multiple specialization we need to have a common language to model them and bond graph provides you this common language which actually across the domain, we can use the same kind of elements to model the system that is one of the advantages of using bond graph methods.

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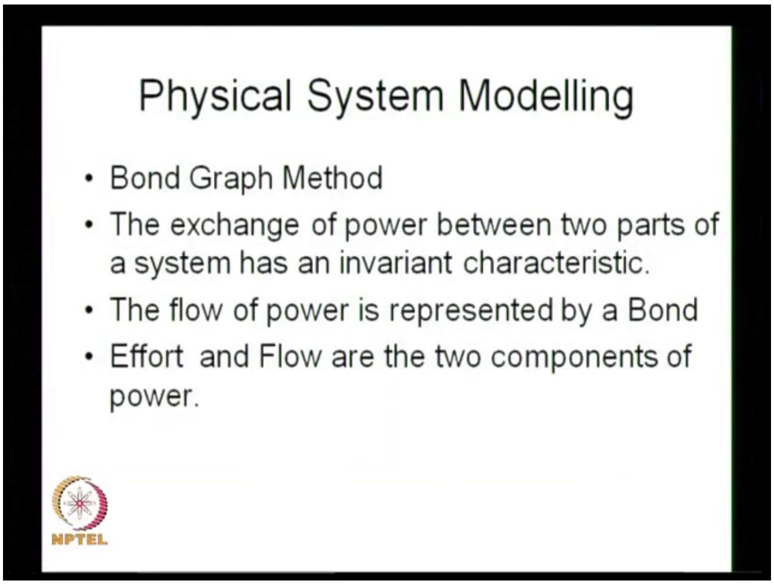

So, as I explained in the previous class, this is actually discuss about the exchange of power between 2 parts of a system. So, whenever there is a dynamic behavior of a system there is an exchange of power between elements. So, we are trying to model this power transfer or movement of power or transaction of power and that is why sometimes it is known as power bond graph method also and here the flow of power is represent by a bonds a bond is represent by a half arrow. So, that direction is represented by the arrow and flow is represented by bonds and as I mentioned effort and flow are the 2 components of power.

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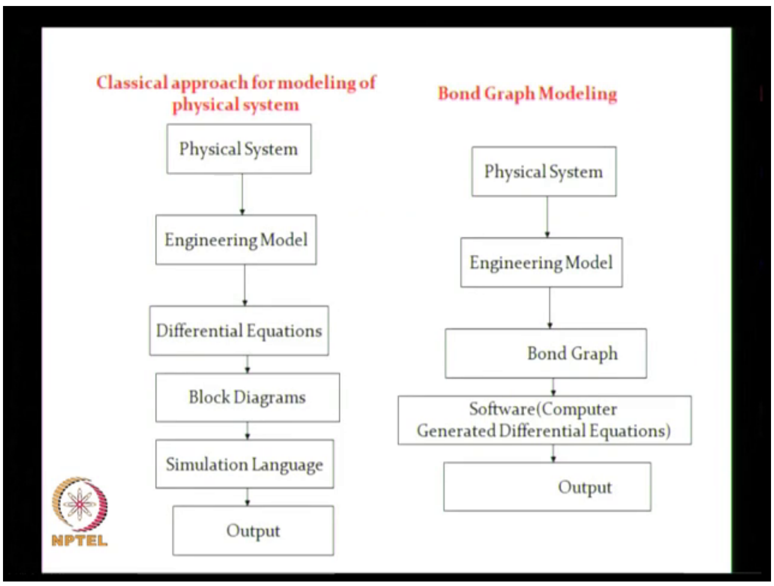

And this diagram, I explained the difference between the normal or conventional way of modeling and the bond graph modeling. So, here basically we do not go for the differential equations instead we directly go for the bond graph models or direct from the physical system, we develop a an engineering model of system and then convert that in to a bond graph and then we can use the standards software for simulation. So, that is the main difference in bond graph and the classical approach.

So, we will actually jump through this differential equation, we do not go through the differential equations we will bypass this because creation of equations and the block diagrams will be carried out by the software itself.

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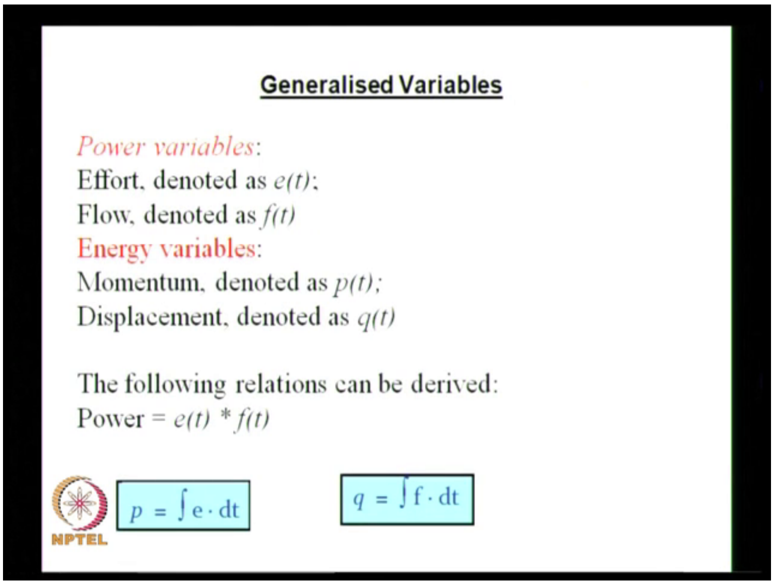

So, we have standard softwares to do the job again coming to the generalized variables for the system we have 2 important variables one is known as the effort the other one is the flow. Effort is normally represented by e and flow is represented by f they are time dependent variable.

So, we will write that as e t and f t. So, these 2 variables actually represents the flow of power the power is obtained by multiplying this effort and flow. So, that actually defines the power transfer between 2 elements the other 2 variables are a momentum denoted by p t and the displacement denoted by q t. So, we can see here the momentum is represented by p and displacement by q and they are not independent the basically p is an integral of efforts.

So, p is obtained by integral e dt and q is integral f dt that is integration of f will give you the displacement integration of effort will give you the momentum for example, if you have f is the velocity then integration of velocity gives you the displacement. So, that is the relationship between the variables f and q and e and p and the power transfer is e t multiplied by f t.

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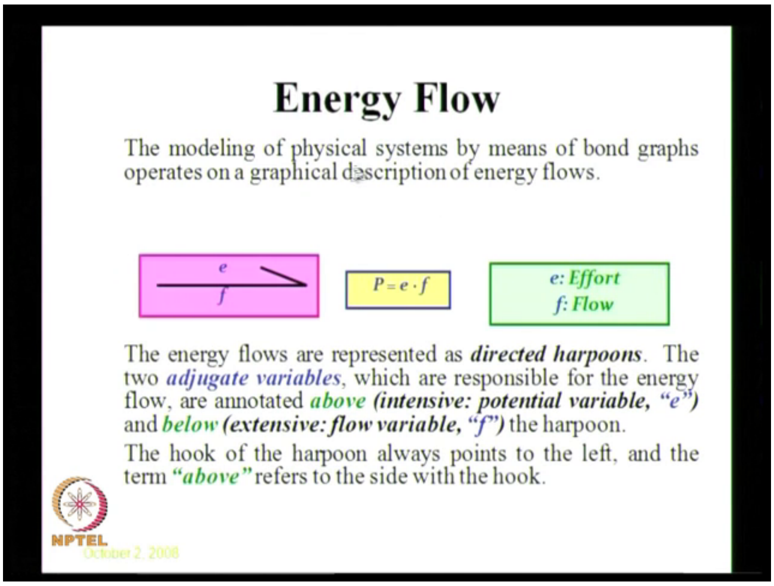

So, these are for generalized variables used in modeling to explain the energy flow. So, the energy flow is represented by as I explained by a bond. So, they are known as directed harpoons. So, the energy flows are represented as directed harpoons the 2 adjugate variables that is the effort and flow are annotated above and below. So, the e is actually above the bond and f is below the bond or the other way you can say that the hook was the harpoon always points the left and the term above refers to the side with the hook.

So, when this is harpoon and this is the hook and this is the above and this is below. So, when it is in the vertical direction then e will be on the left side and f will be on the right side.

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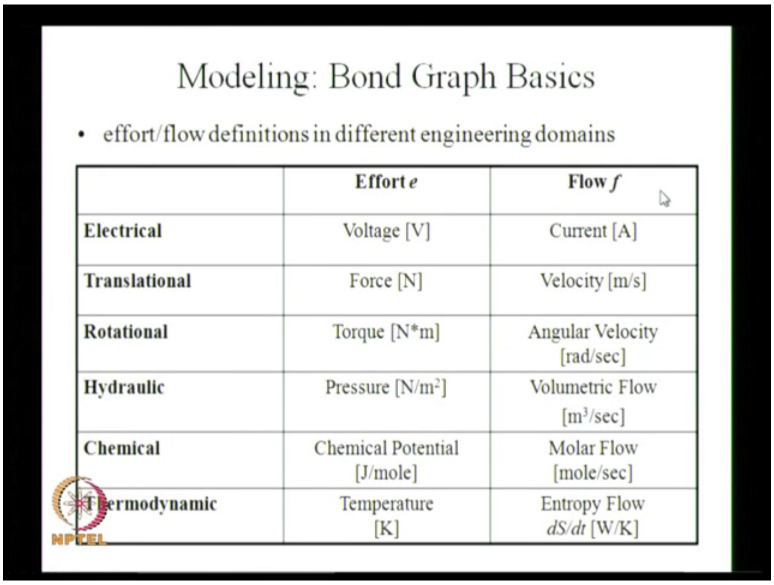

So, this is the normal convention of representing effort and flow for various domain for multiple domains this effort and flow can be defined for example, for electrical effort is voltage and flow is current for translational motion force and velocity rotational motion torque can angular velocity hydraulic pressure and then volumetric flow chemical is chemical potential and molar flow thermodynamics is temperature and entropy flow. So, we can see here for various domains we can still have the effort and flow parameters whether it is electrical system or hydraulic system or a chemical system you can actually represent the effort and flow irrespective of the domain.

So, we do not need to worry about the domain because effort and flow is always the same representation can be used to represent a voltage or a pressure. So, e will be the common for voltage or pressure. So, even if there is a change in the domain still the e and f the representation remains the same. So, that is the advantage of using bond graph.

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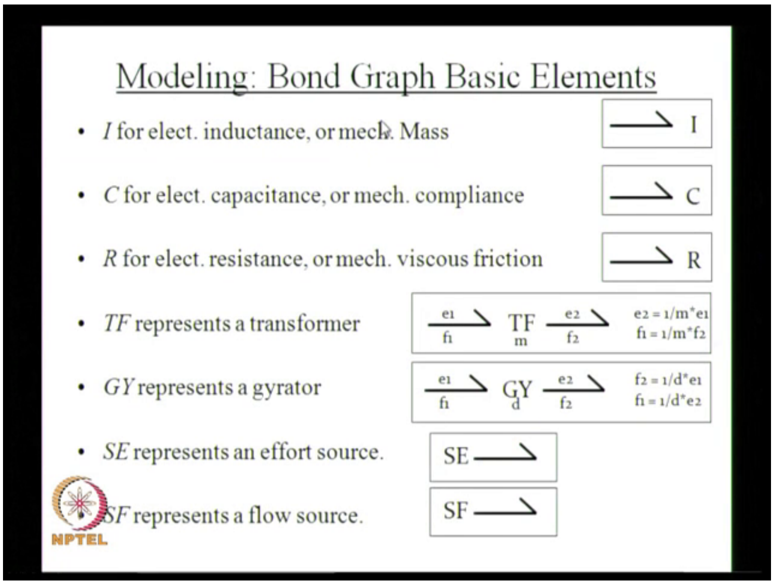

Now, there are some basic elements in bond graph modeling. So, these are the most basic building blocks for making the bond graph the first element is the inductance or I. So, this is actually represents the I element represents the electrical inductance or mechanical mass or inertia. So, any electrical inductance mass or inertia can actually be represented by an element I. So, that is shown in the diagram here. So, this is the representation of an I element. So, we have this I and then a hap bond representing the I element.

Then another element is C or the capacitance. So, this one as inertial element or this is the capacity element. So, this is actually for electrical capacitance or mechanical compliance. So, if we have a spring or a electrical capacitance that can actually be represented by a element C and then R for electrical resistance or mechanical viscous friction here that is the resistance element R. So, these are the 3 basic element of bond graph I C and R. So, I represent the inductance or mass or inertia C represents the capacitance or compliance R represents the resistance or friction forces. So, this are the 3 basic elements and then we have some other elements called TF; TF represents the a transformer.

So, whenever there is a transformation of energy from one form to other form or one some rotary motion to a linear motion or you can have a gear box the rotary motion is transform to another rotary motion with a ratio of power then we can represent it by an element called TF. So, here you can see that TF is e 1 the flow is e 1 and f 1 are the inputs. So, effort one and flow one then you have effort 2 and flow 2 and this TF M represents the transformer ratio and the relationship between e 1 and e 2 is given here e 2 is equal to 1 over M e 1 and f 1 is 1 over M f 2 that is the relationship between e 1 e 2 and f 1 f 2.

So, here e 1 is converted to e 2 and f 1 is converted to f 2 through a transformer you can think of a gear box where there is a change in speed as well as change in torque after the before and the after gear box. So, that relationship can be represented using a element called TF and the gear box ratio can be represented as M the ratio of gears represented by M and the relationship e 2 is 1 over M e 1 or we can say e 1 is equal to M multiplied by e two

And f 2 is 1 over M f 2 f 1 is 1 over M f 2 or f 2 is equal to M f 1 and there is another element called gyrator this actually different from the transformer. So, in this case the relationship is between e 1 and f 2 and f 1 and e 2 basically the effort is converted to a flow and this flow is converted to a effort that is why we use a gyrator for example, if you have an electric motor. So, we give a current and you will get it as a torque output. So, the flow parameter is converted to a torque parameter. So, here is a conversion from flow to effort. So, that kind of relationship is represented using a gyrator element. So, we can see even related to f 2 and f 1 to e 2 and that relationship is given as f 2 e 1 over d e 1 and f 1 is 1 over d e 2.

So, you are relating the f 2 and e 1 and e 2 and f 1. So, that is the relationship for gyrator and there are 2 other elements source effort and source flow source effort is effort source that is you provide a effort to the system as a source effort then that is represented by an s e element for example, a voltage source voltage source can be represent by a a source effort. So, here the source is the effort and that is given to the system then you represent that as a effort source, then you have a source flow or the flow source which is represented by SF where you have a current source or a flow source like a hydraulic flow or any other flow input, then we represent it is in SF. So, you have source effort and source flow which represents the sources for the system that is the input sources with the system an effort source and a flow source then you have a gyrator which represents the relationship between the effort and flow and then the input effort and the output flow similarly input flow and the output efforts. So, that can be represented using a gyrator element.

And then you have the transformer element which actually relates the efforts that is e 1 and e 2 and f 1 and f 2 and we have other power consuming elements I C and R. So, I C and R are the power consuming elements these are the power transfer elements and this is the source effort and the source flow elements. So, these are the basic elements you get for bond graph modeling.

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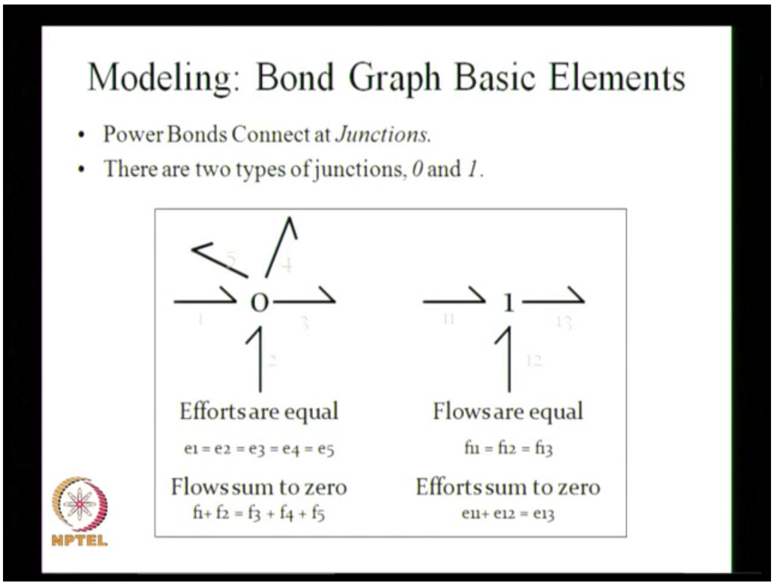

We have 2 more elements which actually represents the junctions in the bond graph. So, whenever you have a junction that is whenever you have different sources coming to one point and then it gets separated so that can be represented using bond graph junctions. So, we have 2 kinds of junctions 1 is known as a 0 junction the other one is a 1 junction. So, you can see here 0 junction and one junction. So, 0 junction is known as a common effort junction. So, the 0 junction the; we said this is a common effort junction because all the efforts are equal in this junction. So, we have 1, 2, 3, 4, 5 bonds here and these 5 bonds all this bonds are having same effort. So, e 1 is equal to e 2 is equal to e 3, e 4 equal to e 5. So, here you have all the bond all the efforts equal and the flows sum to 0. So, the flows were coming inside. So, this arrow represents this flow is coming inside. So, 1 and 2 are coming inside and 3, 4, 5 are going outside. So, whatever the flow is coming inside should be equal to flow going outside that is f 1 plus f 2 is equal to f 3 plus f 4 plus f 5 that is the flow sum to 0. So, that is the 0 junction. So, you have a common effort and the flows adds to 0.

This is something like you have a voltage source many elements are connected in parallel to that voltage source, then we will be getting same voltage from across all the elements, but the currents will be different. So, this actually represent that kind of a scenario then you have another junction called one junction the difference between 0 and one is that 0 is a common effort junction, but one is a common flow junction here you have the flows are equal though the flows in these 3 bonds that is 1 1 1 2 and 1 3, they are all equal. So, f 1 one is equal to f 1 2 is equal to f 1 3. So, all the flows are equal here and efforts sum to 0. So, e 1 one plus e 1 2 is equal to e 1 3. So, you can see these 1 1 and 1 2 are coming to this junction and one 3 is going out.

So, you have e 1 1 plus e 1 2 is equal to e 1 3. So, that is the one junction; now with these elements that is 0 and 1 junctions and you have the source effort and source flow then you have the transformer gyrator and I C and R elements. So, these are the only elements you need to make a bond graph model of any system whether it is electrical system mechanical system or hydraulic system or a combination of this we can model the system using only this elements. So, we have 3 power consuming elements I C and R then we have the transformer and gyrator and then source effort and source flow and 2 kinds of junction 0 and one with this elements we can actually model the complete system using bond graph methods.

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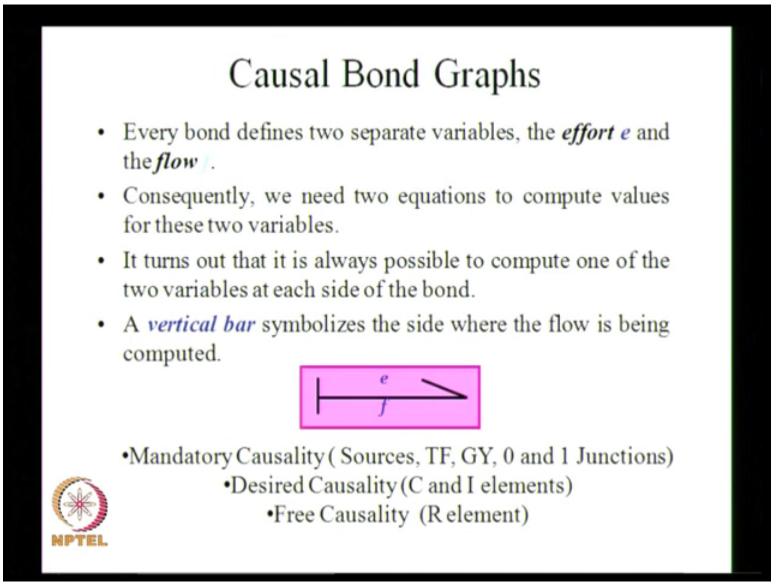

We will see few examples how do we do that, but before going to that we have one and important function to be defined which is known as the causality in the system. So, causality basically it actually explains what actually causes the system to perform. So, whether there is a input is effort or a flow in to that system which actually causes the system to behave. So, that is known as the causality. So, every bond defines 2 separate variables the effort and flow and consequently we need 2 equations to compute the values of for these 2 variables.

So, we need to have 2 equations for effort and flow it turns out that it is always possible to compute one of the 2 variables at each side of the bond. So, you can actually compute one of these variables at one side of the bond and a vertical bar symbolizes the side where the flow is being computed. So, here you can see that the a vertical bar is shown to show the causality. So, wherever this effect vertical bar is shown it shows that the flow is calculated on that side and effort is coming on this side. So, here flow is calculated this side and effort on this side that is the representation for the vertical bar or the causality of the bond there are mandatory causality for sources like TF GY and 0 and 1 junctions and there is a desired causality for C and I elements and free causality for R element I will explain this how do HD give this causality shortly.

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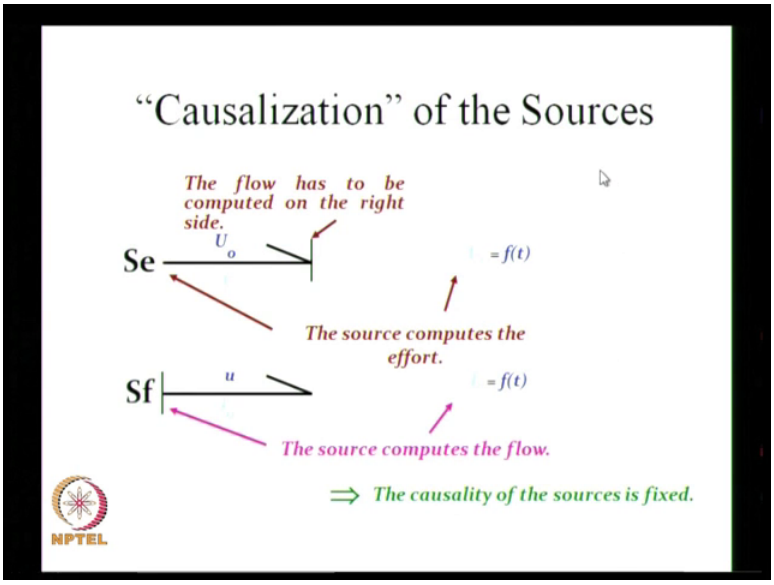

So, here is the explanation for causalization of the sources. So, now, we have this s e and SF s e is the source efforts and SF is the source flow. So, the flow has to be computed on the right side because effort is coming here. So, we need to calculate what is f? So, f is calculated based on the effort. So, you have the effort and it is a it is calculated based on what is the effort coming here calculate f is equal to a function of the effort

Similarly, here source flow; so the flow Sf. So, the causal stroke is here. So, therefore, the flow has to be calculated here and effort is to be calculated here. So, the source computes the flow here the source computes the effort. So, the source computes the effort here and here the source computes the flow. So, that is how we give the causalities stroke and these are the mandatory causality for source effort and source flow. So, the for the source effort you will always have a causality stroke here and for the source flow you will have a causal stroke here at the other end or the left side of the bond. So, here the causality of the sources is fixed Se and Sf you cannot change the causality because here the source computes the effort and then here the source computes the flow that is why this already fixed.

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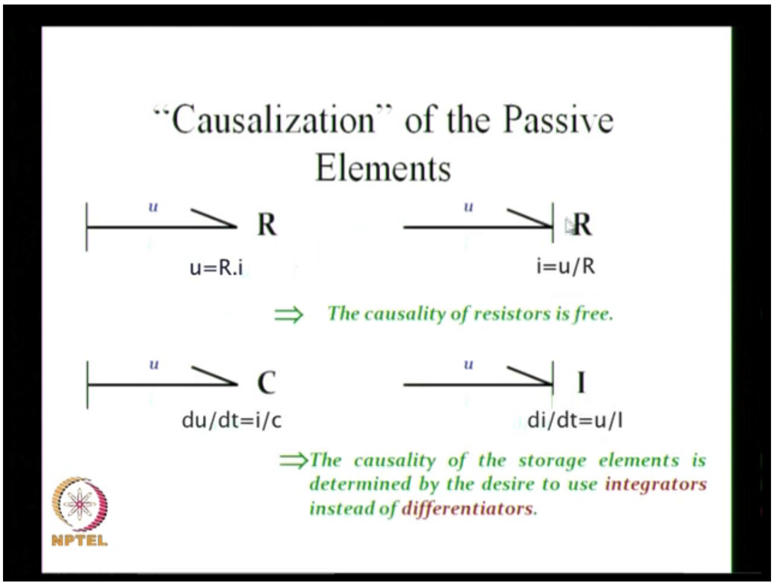

And for other elements to fix the causality for the other elements we need to actually find out the relationship for these elements. So, here you can see this is the R element and for R element we can actually have a relationship like u is equal to R multiplied by I or I is equal to u divided by R that is how you calculate the.

So, here you actually represent the effort and I represent the flow it is the voltage and current. So, now, you can actually supply a current to this element and get a voltage drop. So, I is given as in input and R is given as the output. So, actually you can calculate u is R multiplied by I that is the relationship for this causal stroke. So, in this case the causal stroke is on the left side then the relationship is u is equal to R I.

If the causal stroke is on the right side then the relationship is that the; I is computed u is the input. So, u giving a voltage to the resistance and then you are getting a current flow output. So, I is equal to u divided by R. So, here we are calculating I on this side and here we are calculating I on this side. So, that is i is u by R. So, if you are calculating it on this side then this I is u by R and here it is u. So, R multiplied by i. So, the causal due of resistor is free.

So, depending on the situation again actually provide the causality on this side or this side just this free causality for R elements then coming to the C element here actually you cannot have various causalities because you can have only one kind of relationship here you can see this is at differential relationship du by dt is equal to I over c. So, normally we can actually write it as the 1 over C integral of u dt s i. So, I is equal to 1 over C integral of u dt.

So, that is the relationship you can actually find for this. So, in this causality you will be getting an integral relationship for I we should not go for the differential relationship if you have differential relationship which is difficult for us to visualize the system and therefore, we go for an integral causality and integral causality actually gives us stroke over here which actually tells us that the effort or the u is 1 over integral C dt. So, we can actually find out the output using the integral relationship similarly we can actually for the industrial elements also you can go for the integral relationship where u is obtained as 1 over I integral I dt. So, the flow is obtained as integral of I d 1 over I integral of dt can be obtained. So, that they actually gives you an integral relationship with this causality.

I will explain it little bit more when we take some examples. So, we can understand that this is the integral causality for C and this is the integral causality for i. So, here actually the I calculation is represented here. So, I is actually obtained as integral of 1 over I u and here u is obtained as integral of I over C I that is the flow that is the integral causality for g is to C and I elements of course, in some cases you may find that there are there are becomes a differential causality, but then there are methods to solve that one by providing some additional elements, but in normal cases we always try to provide a integral causality for C and I elements that is about the causality of R C and I elements.

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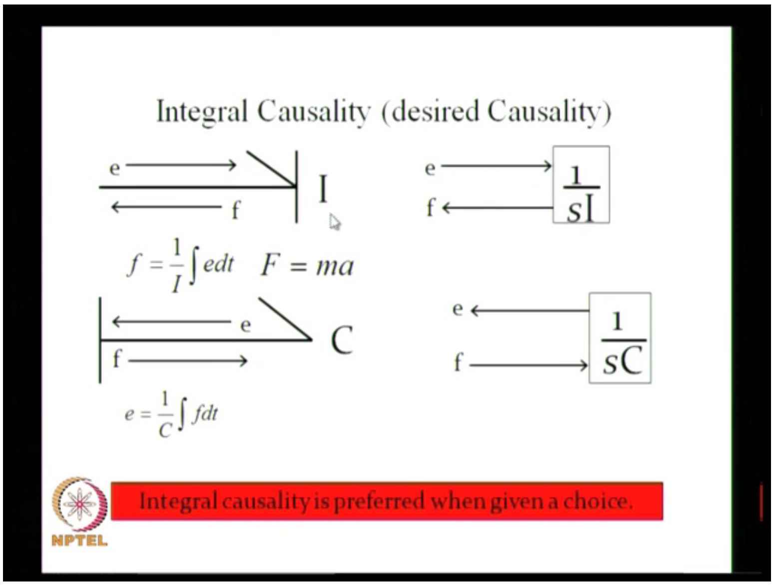

So, this is the relationship for I f is 1 over I integral e dt something similar to the relationship f is equal to M a. So, here f the flow; flow is equal to 1 over I integral e dt. So, the flow is calculated here. So, the effort is the input. So, the effort is coming here and the flow is calculated here f is 1 over I integral e dt that is the integral relationship you are getting and for C elements you can see the 1 over C integral f dt is the relationship that is the flow is calculated here. So, effort 1 over C integral f dt gives you the effort relationship. So, e is equal to 1 over C integral f dt that is the relationship and this integral causality is preferred when given a choice. So, whenever you have a choice you should try to go for the integral causality for these elements.

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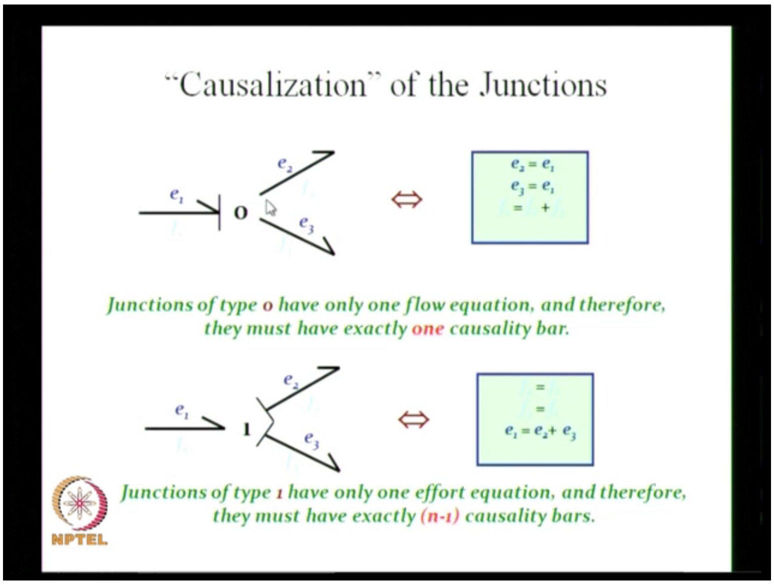

And the final one is the causality for the junctions 0 and one junction as I told you 0 junction is a common effort junction. So, there can be a only one effort coming in to the block to this junction and therefore, we can see that this is the effort coming where the flow is calculated. So, this is the effort coming in that one stroke over here and all other bonds will be without a causal stroke on this end then there will be having causal stroke on the other end. So, that is the causalization of 0 junctions.

So, the junctions of type 0 have only one flow equation and therefore, they must have exactly one causality bar because this there can be only one flow equation we can that is why this is actually one stroke over here and for the one junction junctions of type one have only one effort equation. And therefore, they must have exactly n minus one causality bars. So, here we can see there is only one flow and there is it is a common flow. So, one flow coming inside and then that is common for all the others therefore, will be having causal stroke on all other bonds near to the junction and one without any causal strokes that is the causality for one junction.

So, we can see that f 1, f 2, f 3 are equal and e 1 is equal to e 2 plus e 3 because this is input effort this is the output. So, e 1 is equal to e 2 plus e 3 that is the causal stroke for causality assignment for 0 and one junction. So, we have fixed causality for source effort and source flow then we have preferred causality for I and C elements and we have a flexible causality for R elements and we have fixed causality for 0 and one junctions.

Now, the last one to be seen is the TF and g y elements. So, the TF and g y it is not on here in the slide I will explain it to you using the boards. So, we go to the board and then see how do we actually represent these elements and develop the bond graph model for physical systems.

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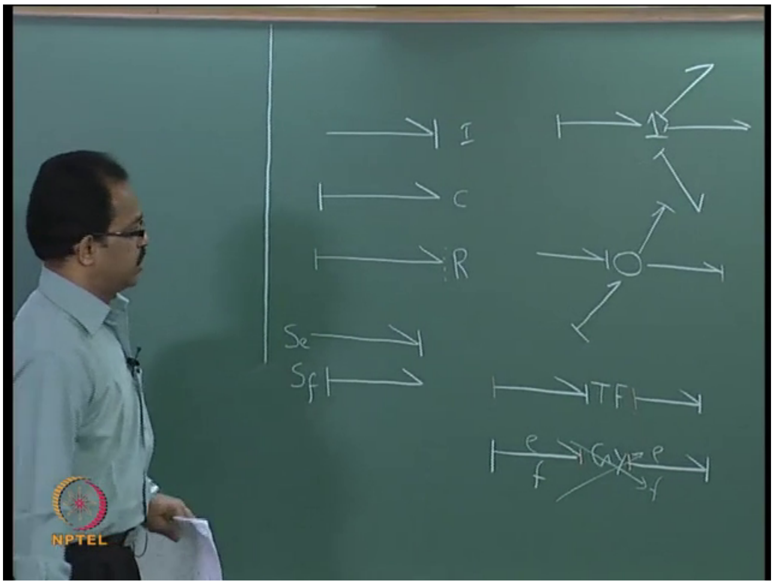

So, as I explained we have this I element with a causality like this and then we have this C element with a preferred integral causality. So, C element and then we have an R element. So, you can have a causality over here or you can have it here depending on the situation and then we have this source efforts. So, this is the source effort and then we have the source flow and we have these junctions. So, we have a one junction. So, in one junction as I told you it is a common flow junction. So, you can actually have one flow there is only one junction only one without a causal stroke and all other will be having causal stroke at this point and then you have this 0 junction. So, here can have only one effort and all others will be here.

So, this is the one junction and this is the 0 junction and the other 2 elements are the transformer and gyrator the transformer we can have a causality like this either like this; that means, the effort the flow is calculated here and flow is calculated here or you can have a causality here also; so, any one of this. So, if this stroke is on this side then here also it will be having on this side. So, you can have either this or you can have this for the causality for transformer and for gyrator it will be like this can have a causality like this here actually the effort is converted to flow here that is why you can have it here. So, this is one possibility causality and the other one is this one you can have a causality like this also.

So, you can have a causality like this or you can have causality like this for gyrator. So, depending on the situation you will have to identify what kind of causality exists for that particular element where it is connected to which junction it is connected to or which element it is connected to accordingly we have to assign the causality for these elements. So, this are the basic building blocks for the bond graph modeling. Now let us take a very simple example and then see how do we actually develop the bond graph model for such systems for mechanical systems or hydraulic electrical systems; let us take the simple example shown in the in the slide it is basically a mass spring damper system.

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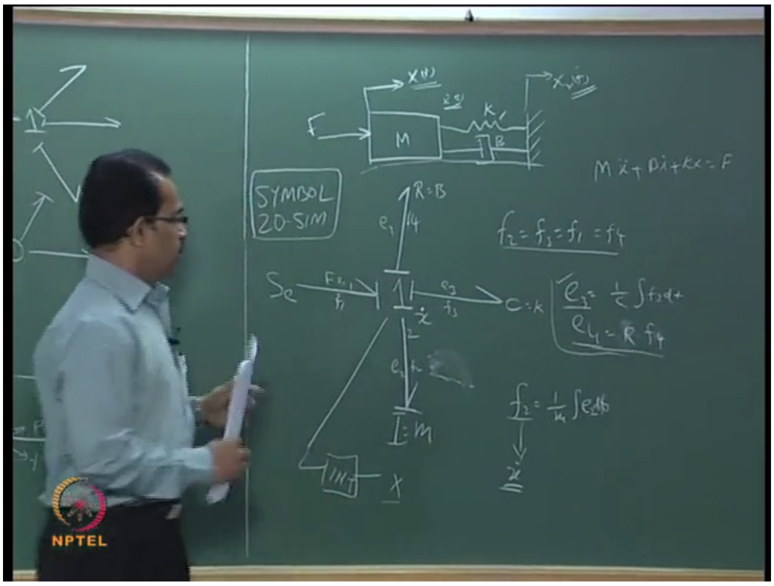

So, you can see here this subjected to f force and then this is the displacement h t and if you can assume that there is a reference velocity also Xrt of course, this is fixed then it will be 0; that means, it can be actually represented x t and Xrt as the reference and this is the mass and this is the spring constant k and this is the damping coefficient b. So, this is the mechanical system if you want to develop a one graph model for this we know that if you do for a mathematical modeling you have to write down the equations M x double dot pursuing this as 0, we can write it as b x dot plus k x is equal to f we can write this is equation and then we need to simulate it and then find out the outputs.

But in the case of bond graph we do not need to really go for the mathematically equations we can actually directly write down the bond graph or the we can make the bond graph and then directly simulate it how do we do this basically we identify there is a force input to the system; so will write down that as a source effort. So, we know that a force input is a source effort. So, it is an effort it is given as a input. So, this is a source effort and we have a causality over here. Now for the time being I am assuming that it is 0 there is no velocity over here that is 0. So, I do not consider that part here now I know that this mass this force is acting on the mass and then this having a velocity displacement x which actually we can write x dot is the velocity here and then this k is having a displacement. So, this is actually this spring is subject to a displacement of x and b subject to a velocity of x dots.

So, we are having only one velocity here which is actually the x dot x dot is the velocity. So, we have a common velocity here which is actually k and b elements they are subjected to therefore, will be having a one junction over here because there is a common velocity junction now will look at now there is a common velocity here and there is a mass attached to this. So, we write down we make a bond for the mass that is I element which is equal to M and then it is connected to k and b the same velocity. So, therefore, we can actually connect it to a C element which actually represents the spring stiffness and then we have a R element which actually represents the damping in the dash board.

So, that is all what we need to do we have completed the bond graph model for this system and what we need to do is to just give the causality assignment we know that I has got a fixed causality as you can see here I has got a fixed causality and then I has got a causality fixed causality C has got a fixed causality and then R can be given like this because a one junction can have a only one bond without a causal stroke at this point it is a common velocity junction and this velocity at here is the x dot x dot is the velocity at this junction. So, we have these source efforts. So, we know that this is a force coming and then this is a R this is the effort this is the velocity of this coming. So, here it is x dot is one by. So, this flow; so, we have an effort coming here.

So, if I number this 1, 2, 3 and 4; I can write it as e 1, f 1, e 2, f 2, e 3, f 3 and e 4, f 4, I can calculate f 2; f 2 is nothing but 1 over M integral of e 2 d. So, that is the velocity or f

2 here f 2 is nothing but x dot. So, we have this f 2 which is nothing but the junction velocity x dot.

So, x dot is calculated and then all others are because of this now we have we know that x dot or this f 2, f 2 is equal to f 3 is equal to f 1 sorry f 1 is equal to f 2 plus f 3, f 1, f 2, f 3 are all same. So, we have all the flows are equal here. So, we have this relationship and now we know what is e 3 we can actually calculate what is the friction forces here e 3 is nothing but 1 over C integral f 3 e t and similarly e 4 is R; F 3 so integral sorry R in to f 4.

So, that is the relationship here. So, we know that all this effort can be calculated e 3 e 4 and we can calculate the flow also; that means, once we know this bond graph we can actually calculate all the parameters that what is the velocity of this what is the displacement and velocity of this mass what is the force acting on the spring that is obtained by here this is the force acting on the spring and what is the force due to friction again we are getting e 4 is R f four. So, all these parameters can be easily calculated using the bond graph. So, our modeling is completed and once we have this model we can actually any software for bond graph there are few softwares available one is known as symbol it is a software available then there are other softwares also that is another called 20 SIM.

These are all commercially available softwares which actually can simulate this bond graph. So, what you need to do is just give a as an input to the simulator then it will calculate all this parameters and you can actually connect the integrator to this junction and it will give you the displacement x. So, here is x dot. So, you will be getting the displacement x from this integrator though it was a very simple system we can show that just by looking at the physical elements we can directly convert that into a bond graph. So, we do not need to worry about the equations. So, this equations are all I explained for understanding basically what we need to know is how it is connected how many junctions are there and accordingly we just connect the elements and complete the bond graph that is all what we need to do in ruling the system.

So, that is a simple example for a mechanical system in the same way we can actually model electrical systems for hydraulic systems also I will take a simply electrical circuit and show how this can actually be bond graph can be used for modeling this I will take a circuits.

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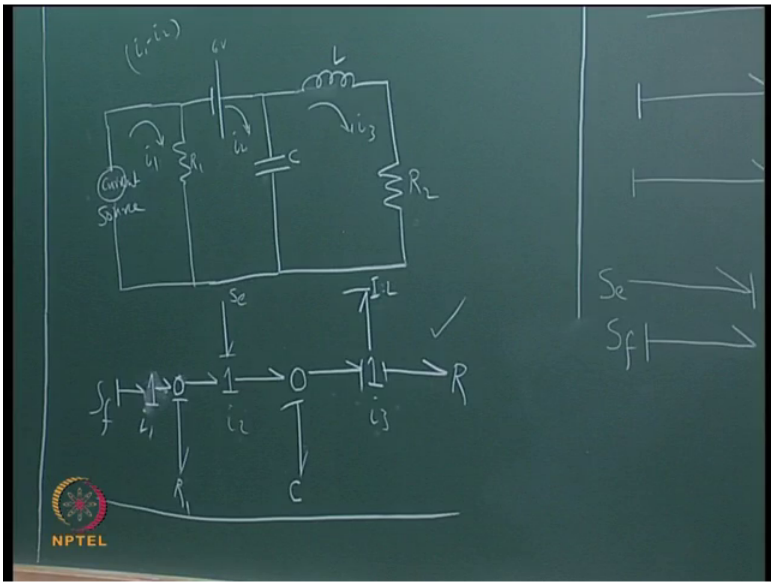

So, we have a current source. So, I show it as a current source and then I connect various elements resistance here a voltage source then a capacitor and inductor a resistor like this. So, we can see there is a current source and there is a resistance I will put it as a R 1 and this is C this is R 2 this is an inductance l and there is a voltage source some voltage source this electrical system can actually be again modeled using one graph we can identify the sources or we have a current source here and we know that there is a current flow this one let us represent it as i 1.

And again there will be a current because of this battery source we can represent it as i 2 and we having another i 3 here we have 3 currents i 1, i 2 and i 3 in this circuits we have a current source here now to model this one we know that there is a current source. So, we start with a SF elements. So, an SF element represents the current source. So, this is the current source SF and its causality is like this. So, will have a R 1 here attached to this one. So, this is R 1.

And the 0 junction because this actually R 1 is subjected to i 1 and i 2 basically i 1 minus i 2 will be the current flowing through this different direction so that actually to be represented. So, there will be a common effort junction here to represent the flow of current i 1 and i 2 on to this element R 1 and then will have a source in I 2 current force and we have a effort source coming. So, we have an effort source that is s e a voltage source active and we have a current flowing from this and that is this i 2 here there will be an i 2 here and then we have this C 2 element that is the capacitor C 2 C element and then we have a i 3 that is a one junction where we have this i 3. So, here this i 2 and i 3 here and this is attach to the R element and or i element. So, i is the l l elements or the inductance.

So, this actually completes the bond graph model for this circuits we can see here of course, we can actually represent here at say one junction and then as a 0 junction, but I simply; I put it as like this you can actually put it like this also to represent this is i 1, this is i 2 and this is i 3. So, we can have 3 one junctions can be separately shown, but when we simplify it actually automatically become this one junction will be removed that is why I did not show it first initially, but you can actually represent this as i 1, i 2 and i 3; 3 one junctions and then we have this R element which actually is summation of i 1 and i 2 or the R will be subjected to i 1 minus i 2 and similarly the C will be i 2 minus i 3; we can see i 2 minus i 3 will be acting on this.

And this will be subjected to i 3 only this current only l and R will be subjected to current only. So, this actually gives you the bond graph model for this electrical circuits again this was a simple circuit, but if you have any complex circuit or of you have mechanical electrical system combined still we can actually develop the one graph model simply by looking at the physical system you can develop the bond graph model you do not need to worry about the equations. And once we have this model we can directly use it in a software to get the outputs what are the output you want you want to find out the voltage across this one or voltage drop of the current flowing can be easily obtained from this one and again you can actually send the causality also here.

This is causality here and then this is the causality and the C has got this causality and has s e has already got the causality and R will be having this causality this is a one junction. So, you will be having this causality here. So, this is the way how we actually develop the bond graph model for electrical and mechanical systems we can actually develop the write down all the equations and develop the state space model for this, but the objective of this lecture was basically to introduce the topic to you not to give a detailed description of how the bond graph method can be used for modeling the system, but just to tell you that this is one of the easiest and good methods for modeling mechanical system of our multi domain systems which can actually give you the performance of this system from the bond graph.

Let me go through briefly some of this models we already explained.

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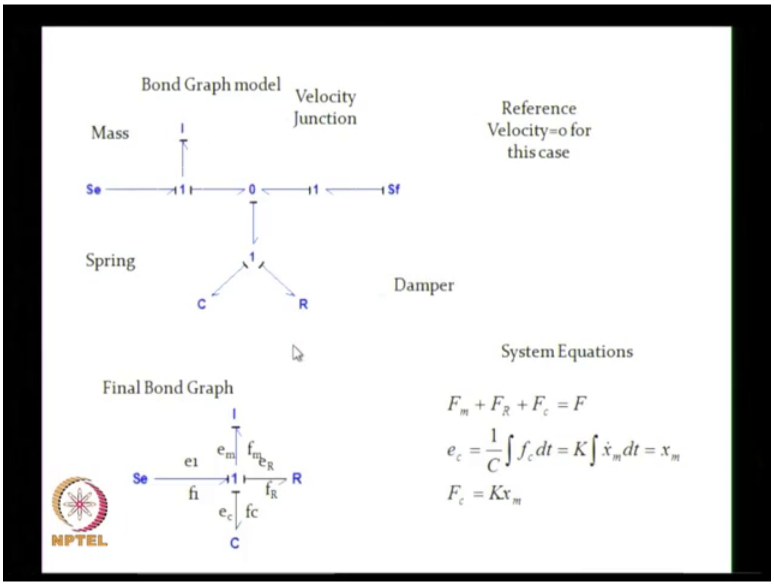

So, this I already explained about this spring mass damper system. So, the finally, it will be getting a model like this and the equations can be written from this once you have this model you can actually feed it in to a software and you can get all the performance characteristics.

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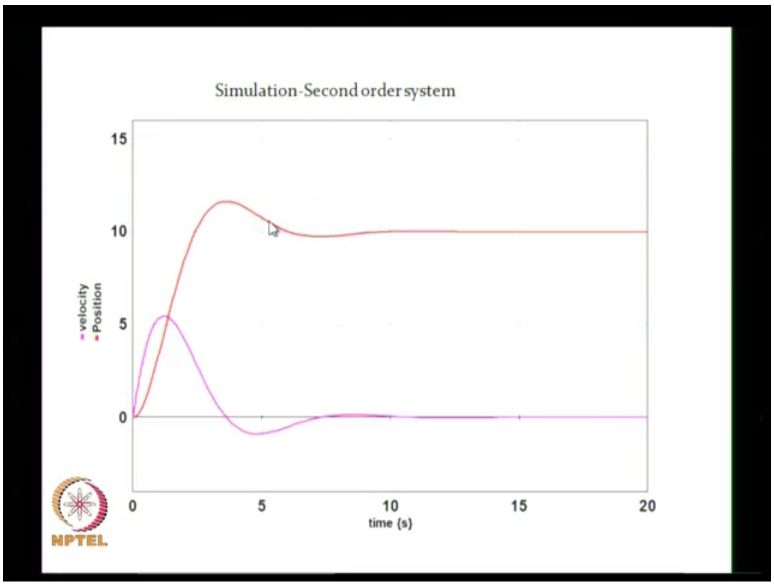

If you know the values of R C and I and the force you apply can actually plot all the performance using a standard simulation software can get the position velocity and any other parameter do you want, you can plot you will be getting responses something.

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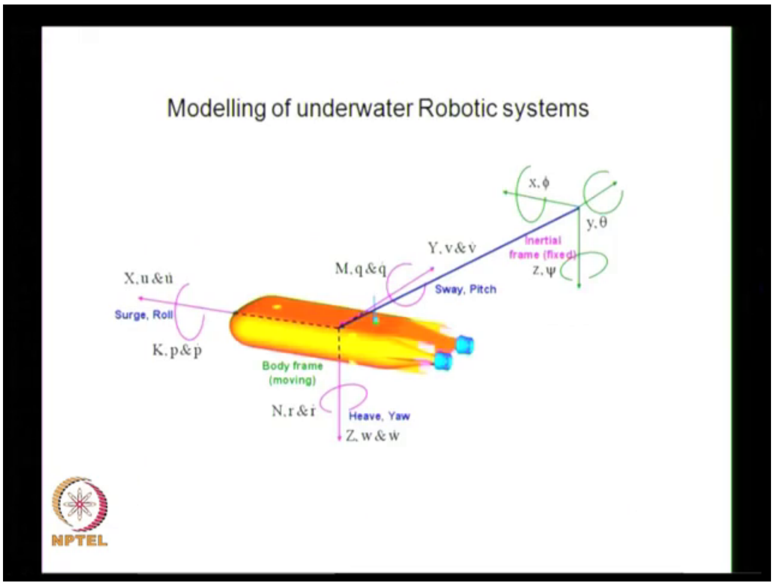

Similar to this just to tell you how bond graph can be used for very complex systems you can just look at this model this is actually a an underwater robots it has got many complex dynamics many sub systems and its own dynamics. So, if you want to represent the complete dynamics of this underwater robot we can use the bond graph method and develop the bond graph model for this and can be used for simulation also I am not going to explain how it is being done, but I can just show you how it will look like.

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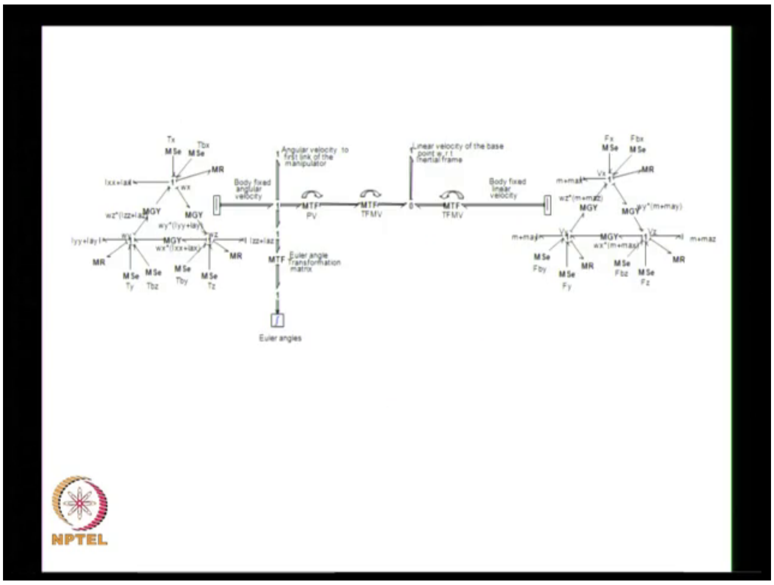

So, the bond graph model for the a u v will be looking like this some of the elements are not familiar to you like this are vector bonds just we have 3 dimensional representation or they have 6 degrees of freedom or motion for the robots. So, we need to represent those parameters like angular velocity and linear velocity in 3 directions. So, if you want to represent then we need to go for vector bonds and. So, if you use vector bonds you will be getting at this kind of a 1 graph for the robots.

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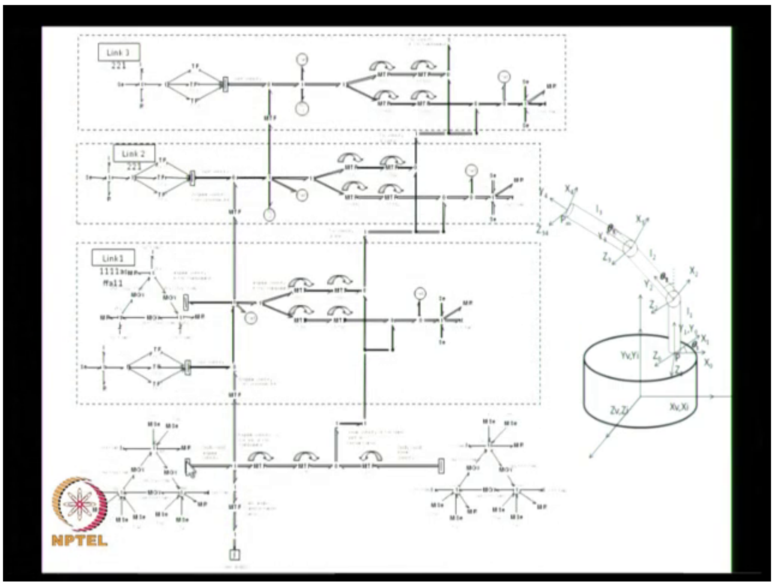

And we can simulate it also and find out what will be the responses and to make it little bit more complex if you have a manipulator attach to this robots we can again still represent the complete dynamics of the robot as well as the manipulator and then find out the response of the manipulator under various scenarios. So, the bond graph will be looking like this; this part actually represents the a u v or the underwater robot dynamics which actually like this here just for representation and this actually shows the dynamics or the bond graph model of its dynamics and this shows the 3 links of the manipulator. So, this the first link second link and third link and you can see the interactions between this links as well as the robot and the manipulator and the a u v can be shown like this here. So, this actually represents the complete dynamics of the a u v and the manipulator using bond graph methods.

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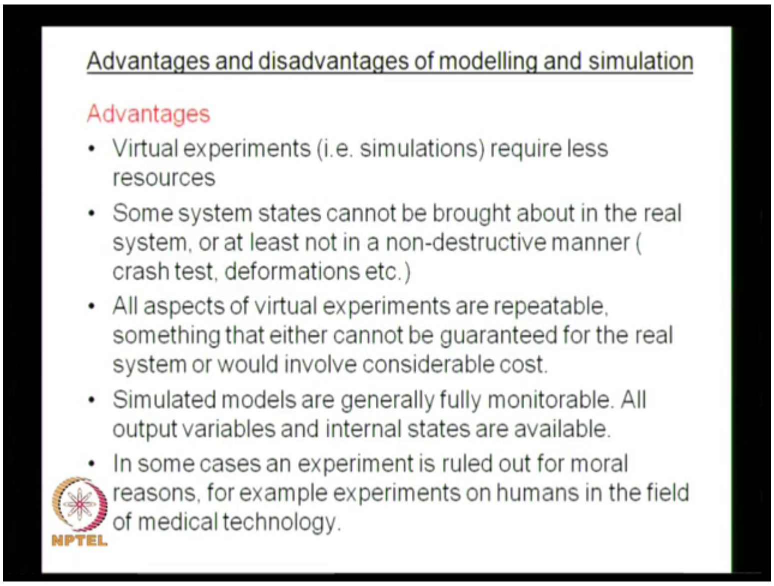

So, to summarize we have many advantages and disadvantages for using modeling and simulation in system engineering basically for various stages we need to use the modeling and simulation tools and we have discussed of few of them tools which can be used there are many other tools also probably you can actually get more information from certain forces, but the advantages are basically we can do virtual experiments without much of resources requirements. So, we have a model we can actually simulate it and find out the behavior without really constructing a an equipment and some system states cannot be brought about in the real system or at least not in a nondestructive manner like crash test and other deformation test cannot be done without destroying the equipment or destroying the sample.

So, this kind of scenarios can be easily modeled and simulated using simulation tools all aspects of virtual experiments are repeatable something that either cannot be guaranteed for the real system or would involve considerable cost. So, the repeatability is an important aspect of modeling in simulation and simulated models are generally fully monitorable all output variables and internal states are available. So, unlike the real systems where actually you cannot monitor all the parameters because you may require hundreds of sensors in to do that, but in the case of model we can actually monitor most of the parameters very easily and in some cases an experiment is ruled out for moral reasons for example, experiments on humans in the field of medical technology. So, in such situations also the modeling and simulation comes as a very good tool for designers.

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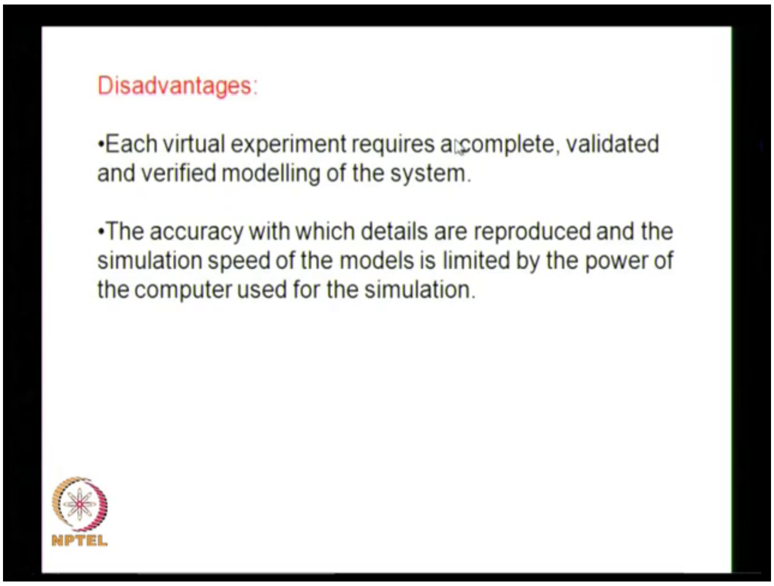

Of course there are few disadvantages each virtual experiment requires complete validated and verified modeling of the system. So, this is one of the biggest challenge how do you make a complete model and how do you validate the model and verify the model whether it represent the actual system or not if it is not representing the actual system, then all your output will be wrong and you cannot make any inferences from this results the accuracy with which details are reproduced and the simulation speed of the models is limited by the power of the computer used for the simulation and again power of the computer actually got some limitations and then that actually limits your experiment the simulation experiments. So, these are the disadvantages of using modeling and simulation.

So to conclude this lecture on modeling and simulation we discussed about the importance of modeling and simulation in system design we discussed few methods like mathematical modeling then data modeling process modeling and behavior modeling and in data modeling. We saw various methods intern process modeling as well as behavior modeling or so. We discussed various methods being used by system engineers during various stages of design process.

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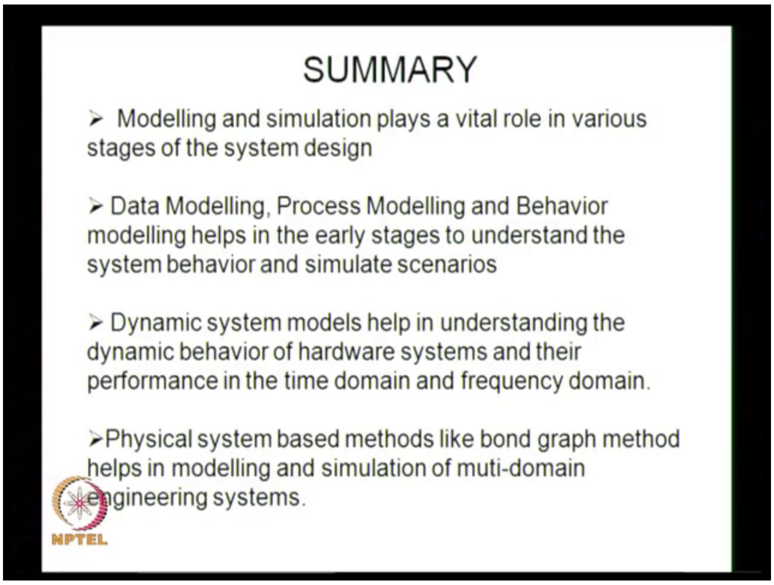

And then we discussed about the dynamic system modeling, especially when looking at the dynamic behavior of mechanical systems or electrical systems or a combination of these systems we saw there are few methods to do that: mathematical modeling can be used or we can go for physical system based modeling like bond graph methods. So, the bond graph method actually helps in modeling in simulation of multi domain engineering systems. That actually concludes this lecture on modeling and simulation. Whatever we discussed it is not complete we have so many other modeling methods and modeling techniques used by various engineers and in various industries. But, this actually gives you a brief idea of how the modeling tools help the system designers in designing their systems and optimizing the system behavior and refining their design systems.

So, in the next few lectures we will discuss more about the other aspects of system design. Basically, looking at the reliability of engineering systems as well as decision making under uncertain conditions what are the parameters we need to consider when we make some decisions in respect of engineering system design.

So, these things will discuss in the coming lectures, so till we meet goodbye to all of you.