Principles of Vibration Control
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Lecture-16
Introduction to Active Vibration Control

Welcome to the course on principles of vibration control. Today we will enter a new resume which is active vibration control.

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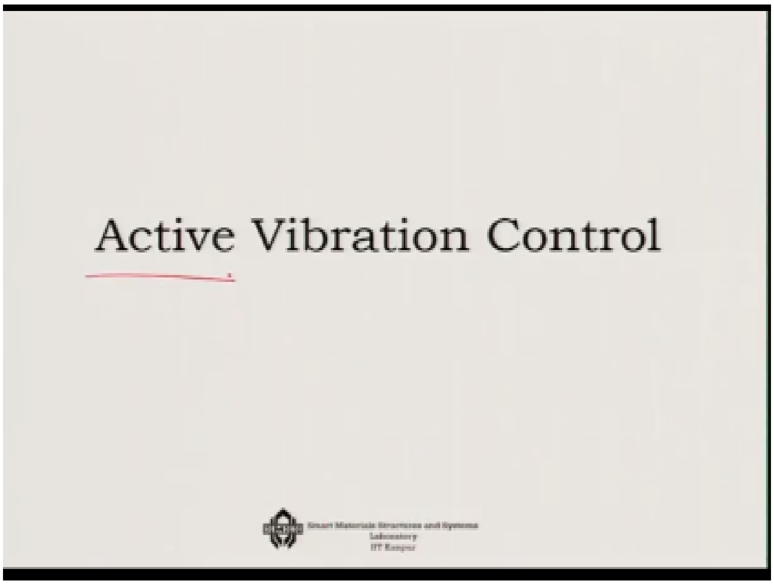

So we will talk about how we can use an array of sensor and actuators and develop some kind of a feedback and feed forward systems and we can control the vibration with the help of such a system. Just a bit of recapitulation if you remember that we have talked about several vibration control strategies in the beginning of these course and the first one in that was reduction of vibration at the source itself.

So which we say that this is the most inexpensive way of controlling the vibration, then we have talked about that vibration isolation, so development of isolation systems are inserting a resilient system, so that the vibration from the ambience cannot propagate. Then thirdly we have talked about system modification and we have said that by read retro fitting or changing the stiffness mass of damping.

You can actually control the vibration. Now this were generally you know passive techniques. Whereas both end we have talked about 2 more techniques. One is a semi passive technique and that is energy harvesting. I am going to talk about a little bit more details on this technique towards the variant of the course again. That is semi passive and finally the active one in which today we will talk about the active vibration control is simply call it AVC using different types classical modern and distributed control technology. So this what we would like to discuss in this ways the course.

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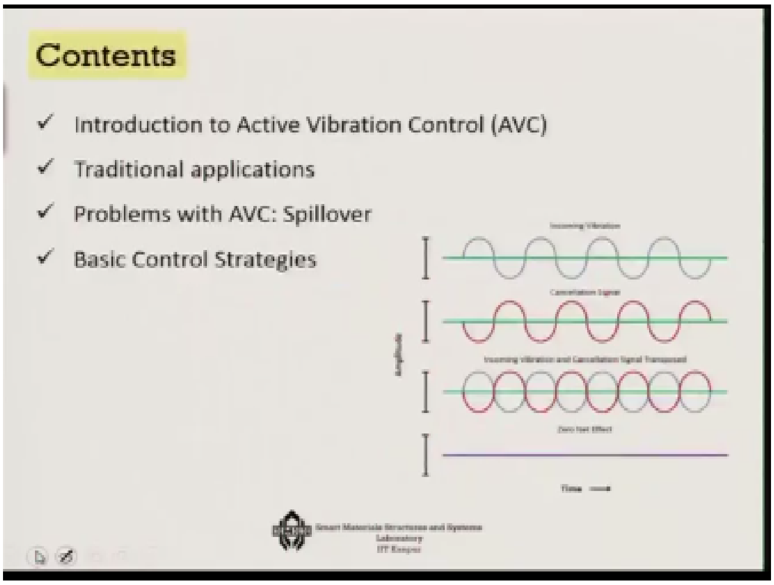

So today I will first give you a brief introduction to active vibration control, will talk about so the traditional applications of this concepts. We will also talk about the problems with active vibration control, particularly the problem which is known as spillover and we will introduce basic control strategies. So fundamentally the active vibration control can be threat of in this manner that suppose you have a incoming vibration.

So this is the incoming vibration signal and then if you are generating a cancellation signal which is just as you can see here that is the just opposite in phase. So that pins in this part it is like this whereas in this part it is just the other way. So this is the cancellation signal. Now you imagine what will happens that everytime it will happen in this manner, okay. So each one of them will be cancel by the other and as a result you get is 0 net effect.

In order to do that, that means you have to know what is the nature of this in coming vibration. For example you have to know that what is the time period or what is the frequency of the system because the cancellation signal frequency has to match with it. You have to also know what is the magnitude and then the cancellation magnitude has to be comparable even if it is not exactly matching.

So you have to know the nature of the incoming vibration and then you have to decide on the cancellation signal. That is the strategy of active vibration control. Now how do I know the nature of the incoming vibration with the help of sensors. So here we will use various types of sensors. For example accelerometer which is very regularly used which senses the acceleration.

And you know also something which senses the velocity like physio electric systems of position. So we need this type of various sensors of these things in order to determine the nature of the incoming vibration. How do I generate you know a kind of a signal, cancellation signal which is almost equal in magnitude to the incoming vibration for that I will need actuators.

So that is where you will need the actuators. There are various actuators again like we will say smart actuators is one this categories that is based on smart materials, that of course there are electrohydraulic actuator there are electromagnetic actuators, there are electro pneumatic actuators, there is a long list of actuators. So with that let us see how this motivation of applying this concept to come.

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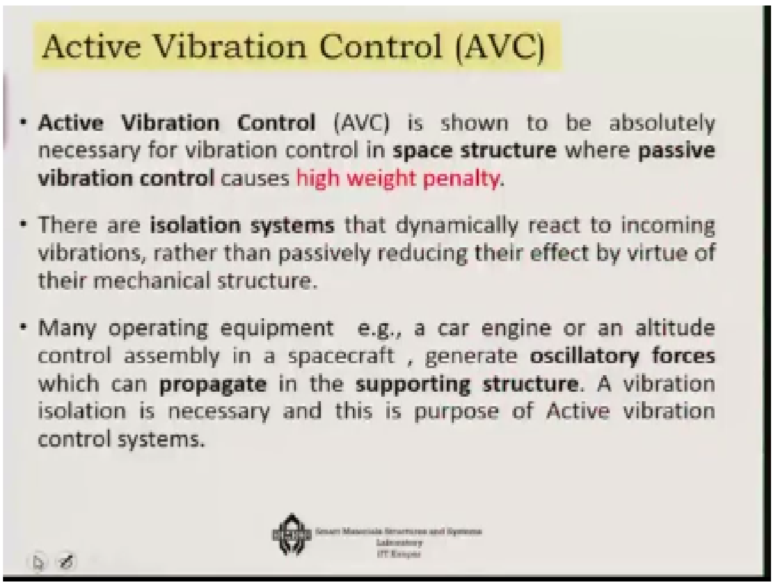

Now this was initially very much important for space structure where the traditional passive vibration control strategy was not welcome because there was a high weight penalty in such a system. So this kind of isolation systems that can dynamically react to incoming vibrations rather than passively reducing their effect was actually you now was a very welcome idea.

Also many other equipment not only for space application like in car engine or an altitude control assembly in a spacecrafts.

In many such things we generate oscillatory forces which can propagate in the supporting structure. For example I told you that in any engine because of the nature of internal combustion engine then will be also this oscillatory force generation. So in such cases a vibration isolation is necessary and using active vibration control system, this can be achieved beautifully.

You can get a much better what you call an active suspension system. You can see some of the examples like Boses active suspension system. So this is the main motivation of the active vibration control.

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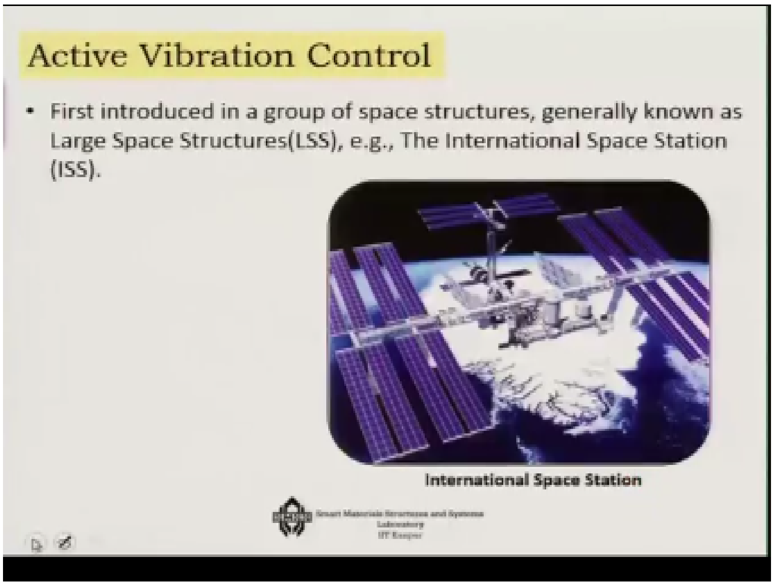

It was first introduced in a group of space structures, generally known as a large space structures. For example the international space station is this space station itself as you can see which is the man based biggest structure in space and they are actually this kind of you know because it is very flexible, so in this kind of a system AVC is detect.

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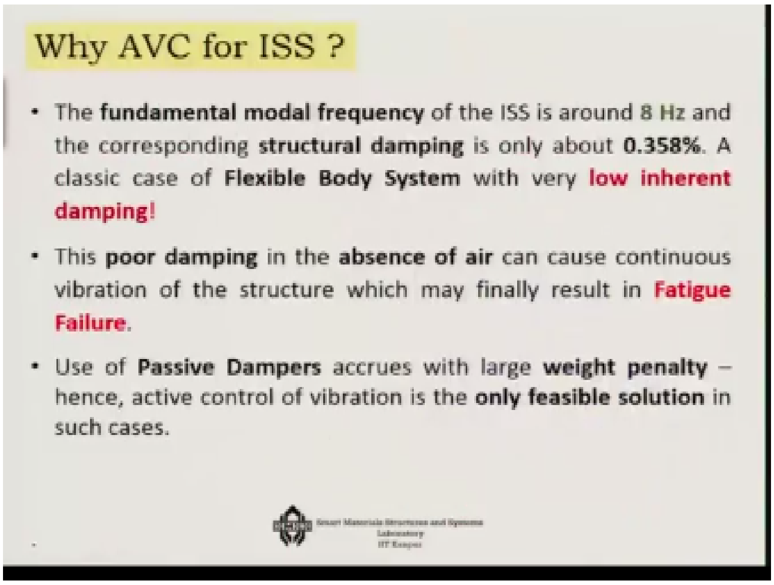

The fundamental modal frequency of this international space structure is about 8 hz and its structure damping is phenomenally low, only 0.358%. So this is the classic case where you have a flexible body 8 Hz you know fundamental frequency is very flexible and once the vibration starts it will not stop because the structural damping is very low. It has a very low inherent damping.

So when there is an absence of air because there is no resistance, so this poor damping can easily result in actually fatigue failure in the system. Now if you try to use passive dampers there will be large weight penalty, also there are issues like in such a low frequency not many passive dampers will be work properly, so active vibration control is the only feasible solution in such cases.

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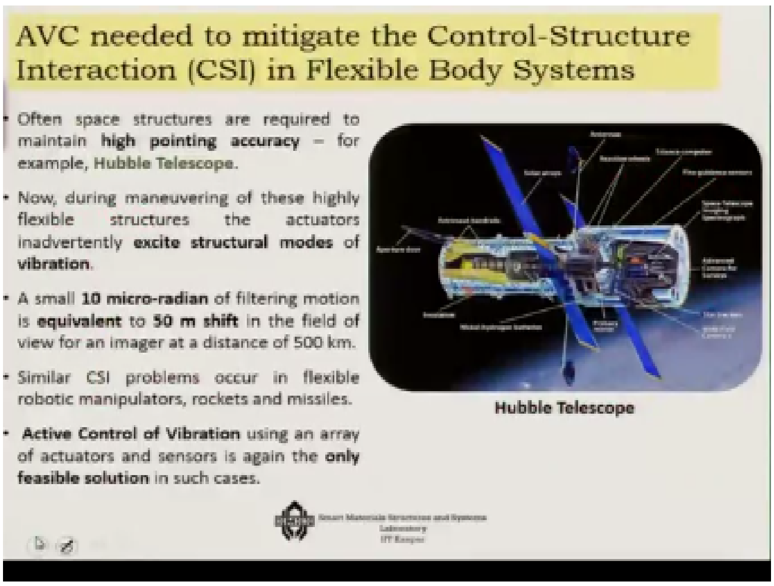

There are also some classical problems which we call as control structure interaction or CSI and that is particularly useful for any flexible body not necessarily for international space station. So one of the examples is where for example you need a very high pointing accuracy like in Hubble Telescope. Durgin maneuvering of Hubble Telescope you now if you excite in an inadvertently the structural modes of vibration.

During any such maneuver emotional as you can see the Hubble Telescope here with so many complex parts in it. A small 10 micro radian of filtering motion will be equivalent to a 50 meter shift in the field of view and that you now for an imager at a distance of only 500 km. So you can imagine how much will be the huge change in terms of its filled of you because only within 500 km itself there will be a shift of 5 m.

So if you talk abut you know millions of km how much of shifting it would happen. So naturally you need a very high pointing accuracy of this flexible structures even though it would be subjected to vibration. So active control of vibration using an array of actuator and sensors again is the only feasible solution in such cases.

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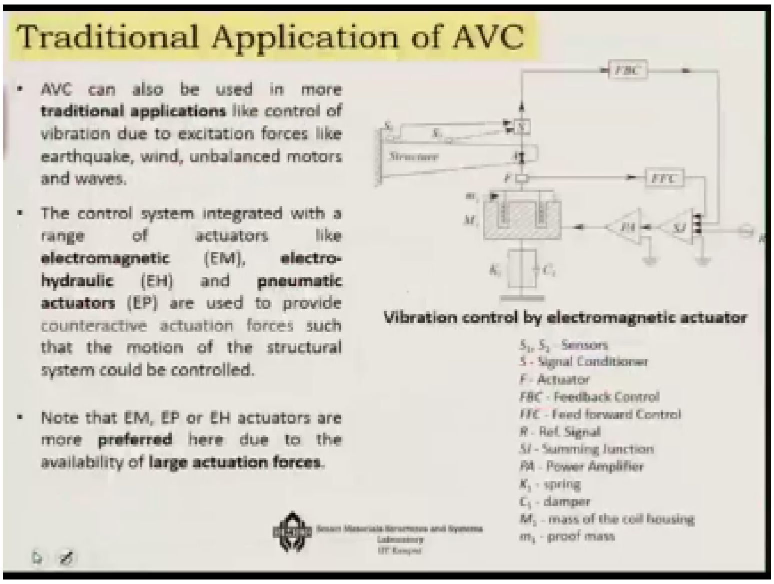

There are many such examples there is one traditional application of AVC that I want to tell you. It can be used in applications like helicopter rotablade, so this is typically one of the you know kind of a continuer beam which represents the helicopter rotablade. Now in this system you can use control system intergraded with electromagnetic, electrohydraulic, or pneumatic actuators and for example you can see here that you can have sensors which can sense these signals.

And then all the same signals come through operational amplifiers and there is a power amplifier here and then there is an actuator here. This actuator here right now is an electromagnetic actuator. That you can also have electrohydraulic or pneumatic actuators in that type. So depending on the sense signal the force is actually given to the system such that the vibration can be controlled in the system. So this is a traditional application for helicopter weak.

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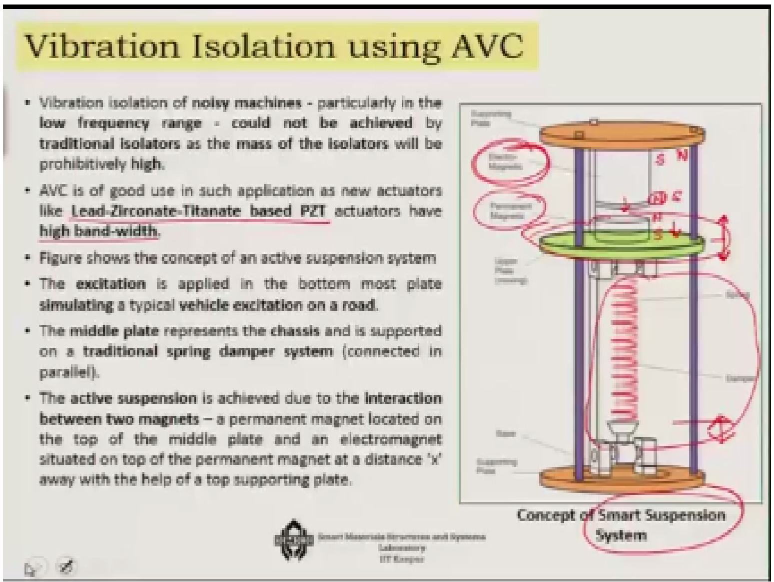

There is another popular one it is based on the control of the magnetic levitation and that is for example in this particular cases you can see that there is a spring here and the spring was damper system, is a traditional system and this is a place here and the plate has a permanent magnet in it, okay. So the whole system is resting on this spring damper system and it is a single degree of freedom system, which has a permanent magnet in the top.

Now this base I can subject it to some kind of a basic excitation problem which is very typical of you know is kind of vibration isolation systems and whenever this vibration takes place I can control the current in the electromagnet, so that these suppose this is a north and south polarity, so that I can generate a north south here. So that I do not allow the magnetic force means top these 2 groups beyond a certain point.

Because a north pole will start to repel each other, so similarly once it is going down in that case once again you convert this to south and north and you attract it, so that it does not go down also. So both for upward as well as for downward movement you control this movement with the help of electromagnet you know the magnetic filed of the electromagnet. So this is the very traditional application of the system.

You can instead of using electromagnets today you use things like PZT actuators which has a very large band width and is also much faster and less noisy than these kind of a system. But this is a typical of a smart suspension system, this is the way it actually behaves.

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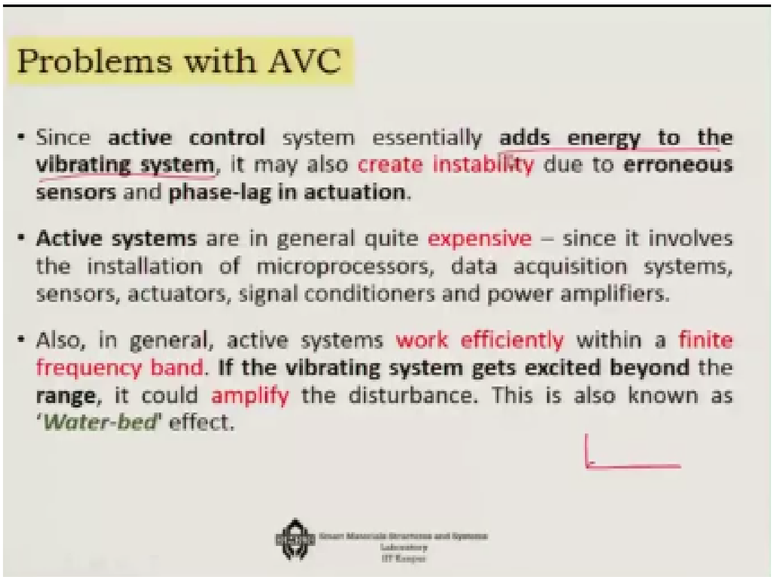

Now what are the problems with this active vibration control system. Since active control system essentially adds energy to the vibrating system, we have seen now what is the disadvantage of this active vibration control.

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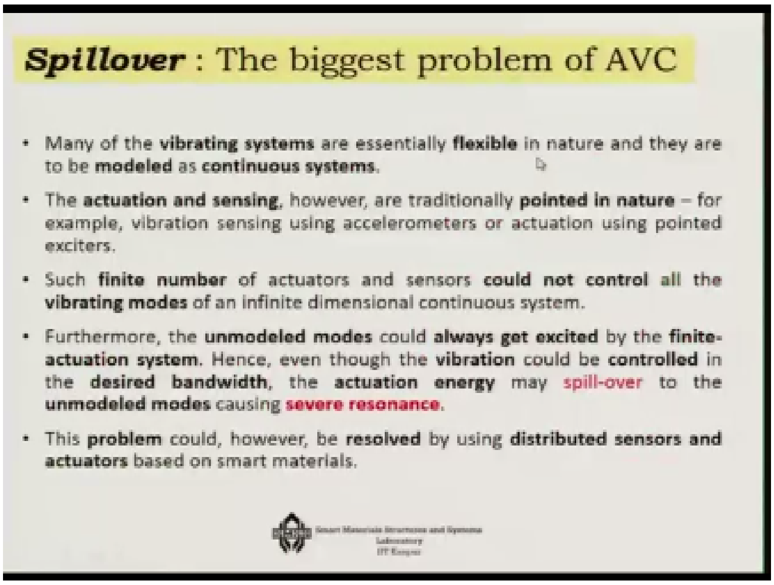

Well active vibration control has certain basic problems for example it adds energy to the you know vibrating systems, so it may also create instability because it is adding energy to the system. Consider that you have the active vibration system which is adding you know which is working on a vibrating system which is having a motion like this and it is suppose to so that means at this moment the structure is going up.

So it is suppose to add a downward force to cancel this motion. Now if by chance instead of this downward force if the phase get cheap and it adds an upward force then this amplitude will become double. So instead of controlling the vibration you know we are going to have higher and higher level of vibration. So that will work, that is what will create actually instability in the system.

So this happens during this erroneous sensor or there is a phase lag in terms of actuation, that means actuation is working slowly instead of you know quickly actuating the system, it is working with a delay. So then this kind of problem would happen. The other problem with AVC is that that this systems are generally quite expensive because you now need a set of sensors, you need microprocessors, data acquisition systems, along with the sensors.

Actuators, signal conditioners and power amplifiers. So it is quite expensive systems. And also active systems work efficiently within a finite frequency band, say for example you have a particular frequency range you know omega with respect to suppose the transfer function if we plot and it is like this and you have designed your active controller for this region. In order to take care of the particular you know resonance act close to this peak frequency.

But then what happens is that in the regions where you have not designed it, these path you now may get modified that means you will start to get a new peak here and that means pumping this is also is known as water bed effect, that means pumping energy to the other places where is not desire. So this may create a severe problem which is also known as spillover problem.

That this is what one can identify to the biggest problem of AVC. That instead of controlling the vibration this spillover generates a new trouble into the system. This many times happens because vibrating systems are essentially flexible in nature and they are generally modern as continuous systems. Now a continuous system has accountably infinite number of natural frequencies in them.

But we are not modeling a system against infinite number of natural frequencies of following range of a frequency. So this actuation and sensing that we have traditionally that then pointed in nature and the work for the finite number of actuators and that is why the could not control all the vibrating modes of an infinite dimensional continuous system. And the trouble is that the unmodal modes could always gets excited by this finite dimensional actuation system.

Hence even though the vibration could be control in the desire bandwidth the actuation energy may spill over to the unmodeled modes coursing severe resonance. This problem however there is a technique to resolve it which is known as distributed sensing and actuation based on smart materials. But it is quite difficult to implement. So spillover is one of the biggest problems of active vibration control.

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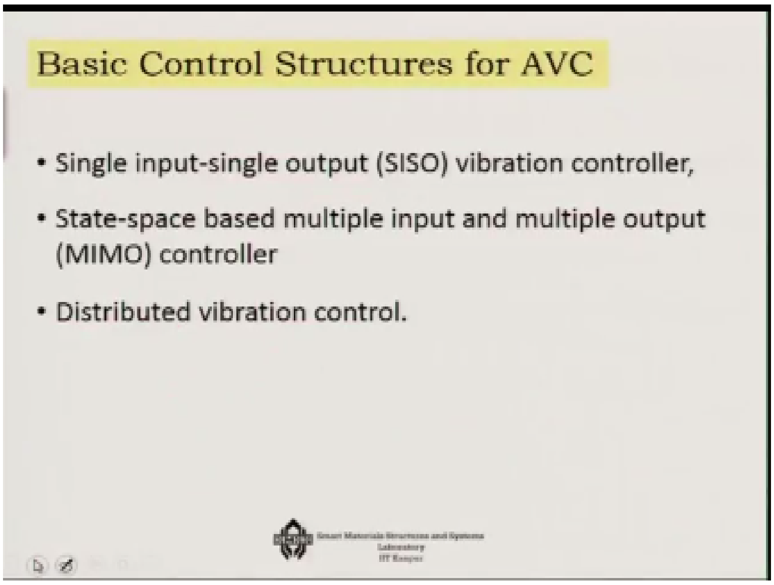

The basic control structures that are used for AVC or single input-single-output that is also we call it as SISO state. A state space based multiple input and multiple output we also call them as MIMI controller and finally the distributed vibration control. So there are 3 different controls strategies that we can use in terms of controlling the vibration control.

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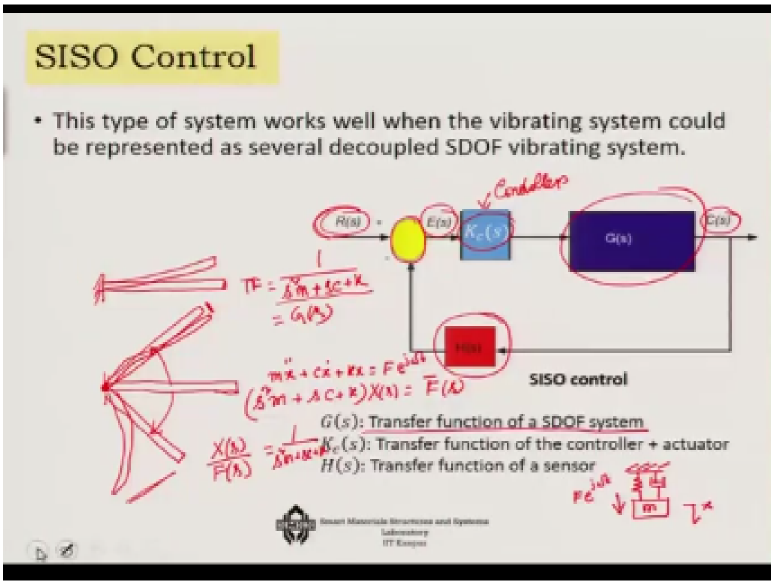

Now first let us talk about the single-input-single-output controller or SISO control. So if you have a reference signal for example you may or may not have if it is just a vibration problem of something like a cantilever beam which is vibrating and you want to drop that vibration down, that is one type of a problem. But in another group of problems instead of having these and you may have a link actually and you have a flexible arm.

And where the job of the flexible are may be in an assembly process is to rotate the whole system from between. 2 positions. Now this is the rigid body movement. This is the reference signal. That you are giving to the system. The reason of applying an active vibration control in this system is that due to flexibility in while movement it can start to vibrate. So may give you this kind of radius vibrating modes.

So that means you will loose the pointing accuracy you now corresponding to various types of vibrations. So that is where the reference signal is to be strictly followed and the active vibration control signal has to work. Now in the single input-single-output system the Gs here is actually the plant that means the transfer function of a single degree of freedom systems. But can be a typical transfer function of a single degree of freedom system let us think of it.

Suppose we have something like this kind of a structure that a spring and a damper and a mass M. So the mass M is actually having a you know response here X and when it is subjected to some kind of the hormonic excitations as we have done earlier as Fe rest to the power g omega t. So we know that the equation of motion of such a system we have discussed about it earlier is Mx double dot+ex dot+Kx=Fe rest to the power g omega t.

In the frequency domain representation this itself will take the shape of S square m+s c+k xs= fs. So in this case the transfer function that is the output to the input relationship will be 1 over s square m+sc+k right. So if I write it in a very nicely here that transfer function will be one over s square m+sc+k. That is what is my gs in this particular case.

You may notice that in this particular case the gs is the second order transfer function so that is what is the transfer function corresponding to the plant. Now we are applying sensors which is going to sense the displacement of the system for example and then the sensor may have its own dynamics that is hs and we are feeding it back so this is the (()) (22:25) junction that the error between the response reference signal.

And these sensed is called the Es, then we apply a controller. So this is the controller in a single degree of freedom system. And this controller then tunes the signal and fits it in to gs, so that it actually gets properly actuated and it can follow this reference signal. If it is if the reference signal is 0 we call it as a regulator problem that means you are just controlling the vibration of bringing it back to the neutral step.

If it is non zero then it becomes something like a guidance problem in which there is a reference signal and the importance is the vibration to be rejected and the reference signal is to be followed. So that is the SISO control of the system.

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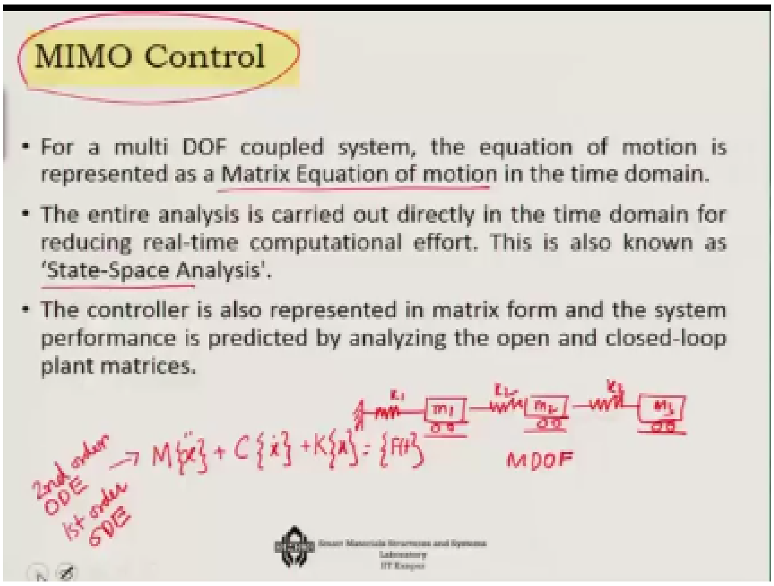

Now whatever we do with the SISO system can we you know extended to a multi degree of freedom couple systems. So that means you know you consider this kind of system that you have 1 mass M1 K1 you have another mass lamping M2 K2 you have another 1 M3 K3 I am just neglecting the damping right now, this part is friction less let us say. So this is a multi degree of freedom system.

So that means instead of getting one single equation of Mx double dot+cx dot+kx equals to something you are going to get a matrix equation here. So you are going to get a matrix equation of motion in the time domain. This type so that means our equation now will be something like M capital M which means it is a matrix and then the vector form MX double dot+ if there is some damping I have not shown any damping in this module.

If it is there cx dot+Kx equals to ft. So that is our matrix equation of motion. Now this kind of systems can be easily as this is the second order you know system, this is the second order Ode in the matrix form you can actually break it into first order ODE and then what you are going to get is actually a state space form of the system. And in that form when you will be controlling it then this is known as multiple input, multiple output control.

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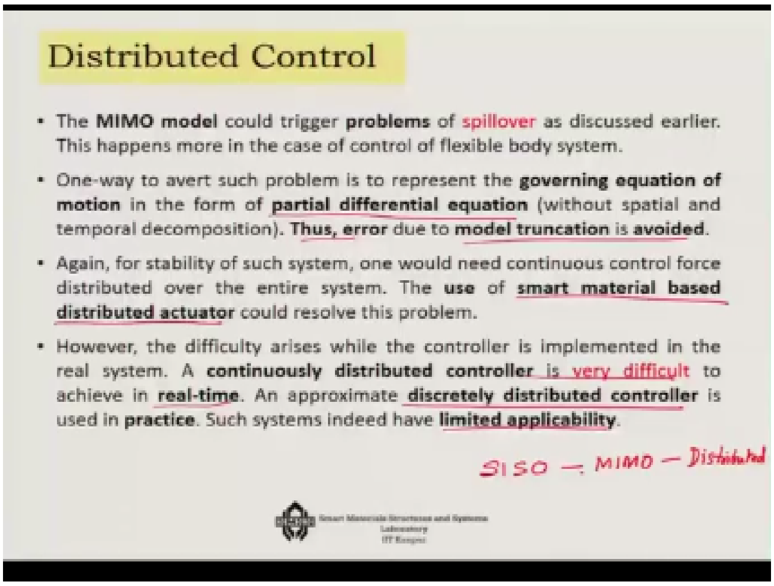

We will talk about it in one of the next lectures. The last type of control strategy is actually distributed control strategy. In this case we are considering the governing equation of motion in the form of partial differential equation itself. So instead of considering the ODE we are going to consider the PDE. So then the error due to model truncation will be avoided. And usually the material based distributed actuator systems is typically suitable for applying this kind of a distributor controller.

So it is generally very difficult to implement in real time but what you can do you can develop a discretely distributed controller which can have a limited applicability. So thus there are these 3 types of control strategies which we can adopt a very simplified one that is SISO, slightly more complicated that is MIMO and more complicated that is distributed controller.

We will first see that how for SISO we are going to use these strategy for active vibration control, then we will see for other type of control strategies.

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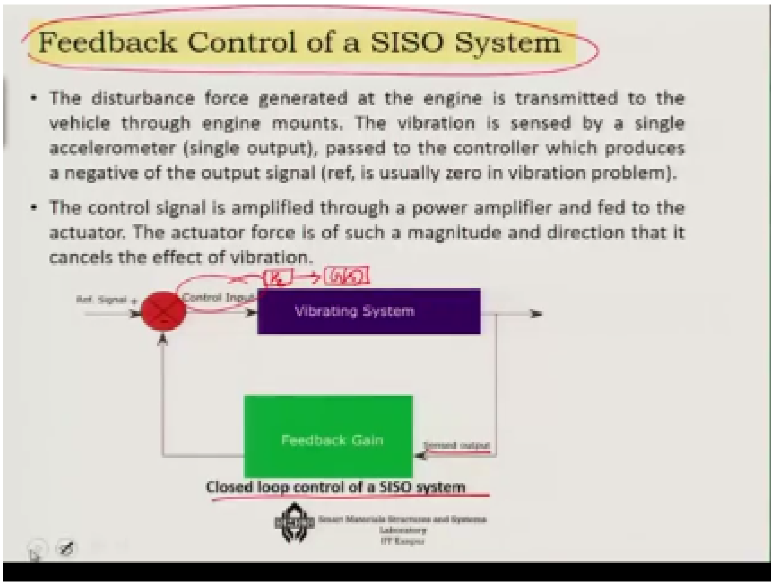

So first we are going to concentrate on the feedback control of a SISO system for vibration control. So here is this control structure again you have the vibrating system, you have a control input here, so that means the controller is actually integrated here, so if you remember that you have this Kc there and there is this plant gs all of them let us say that they are integrated in this vibrating system.

And the feedback gain is here if it is unity then directly you are getting the same output and you are exciting this structure in a close look manner, so that is what is the close loop control of a SISO systems. Usually for sensing I told you that accelerometers are used and for actuation you can use electromagnetic, electrohydraulic, or physio electric actuators.

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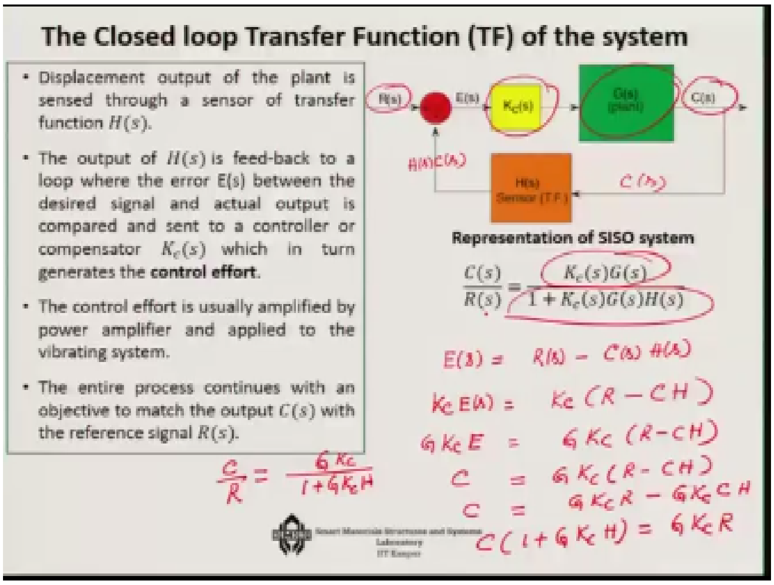

Now what will be the close loop transfer function of such a system. If you look at any basic control book of closed loop control of a classical control then you will be able to you know get this let us try to get the same system, so as you can see here that initially we start with rs okay and then the difference between rs and the sensed output which is cs here and once it passes through this transfer function it becomes hs cs.

So my Es the error function is actually rs-cs hs and this error function I am applying passing it through the controller so it becomes kc es so that means it becomes kc r-ch, all the ss and implicates so I am just taking it out. Finally it is going through gs so then it becomes gkc e that means it becomes GKc r-h, but what is my gkce this is nothing but the cs itself, so actually this gk ce can be written as c equals to g kc r-ch.

And now are we need to do is little bit of rearranging the things that means c equals to gk cr-gkc ch so that means c into 1+g kc h equals to gkc r, so that means my output c over input r is nothing but g kc over 1+g kc h. That is what we have written here kc s gs over 1+kcs gs hs, so that is what will be the close loop transfer function of this particular system.

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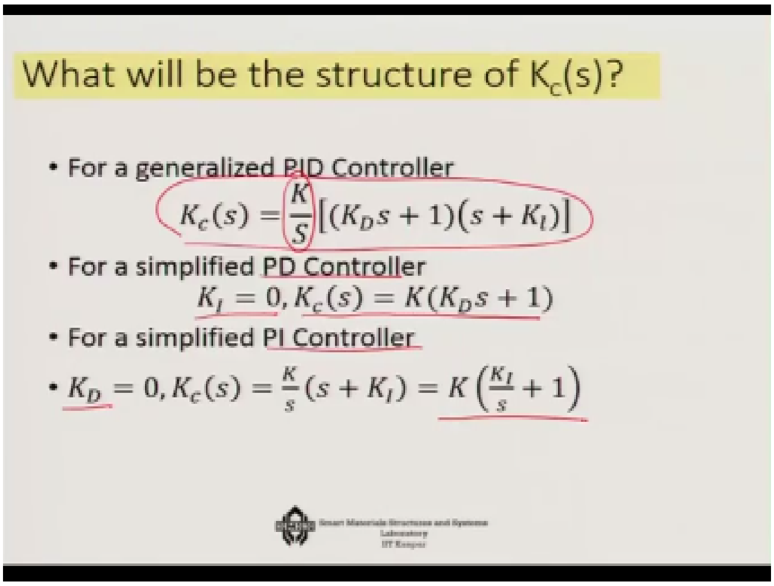

Now with this model you know we can have various types of kcs we can try for example we can try this type of kcs which is a PID kcs which has some integrator this is the integrator part of it and then you can have a differentiator and the proportional part of it. So again you can have some something you know similar but little bit simplified kis 0 you can have and then you can have kcs this is known as PD controller.

You can have a PI controller well Kd will be 0 then this will be the form of it. So you can try various types of kcss as PID, PDN, PI controller. And with that you can actually try here there is a very simple system like a single degree of freedom system which is subjected to unit step input. And let us say that I know what is this stiffness, I know what is Kd, I know what is Ki in this particular case, in this case of this K is proportional part, so this is kp, so I know Kp, kd, and ki that means I know the controller structure.

And let say the system parameters are M equals to 0.2 unit, c 0.0001, k 0.5 and h is equal to 1. Assume a unity feedback system.

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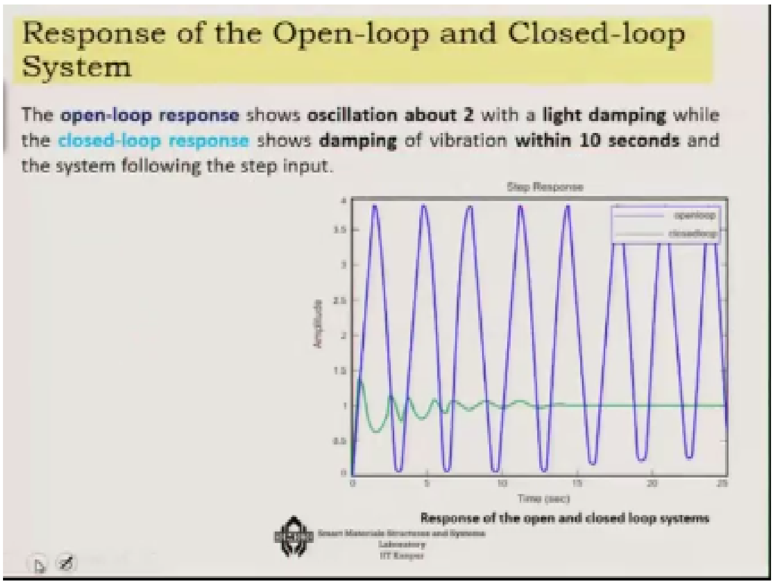

So with this system if I apply this particular controller then what is going to happen, you will see that in the open loop such is the amplitude huge amplitude, whereas the step signal that it has to it is suppose to follow in the close loop system once I close it you can see that within about you know oscillation of about 2 cycles itself within something like a 10 seconds, somewhere like this.

You are already started to follow unit step signal. So that is the beauty of application of the active vibration control. This is where we are going to you know close today.