Micro and Smart Systems
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Lecture - 06
Smart systems Application & Structural Health Monitoring

Today, we will talk about the smart systems and its applications and also one of the critical applications in the area of structural health monitoring. This is the lecture 6 of the micro and smart system course.

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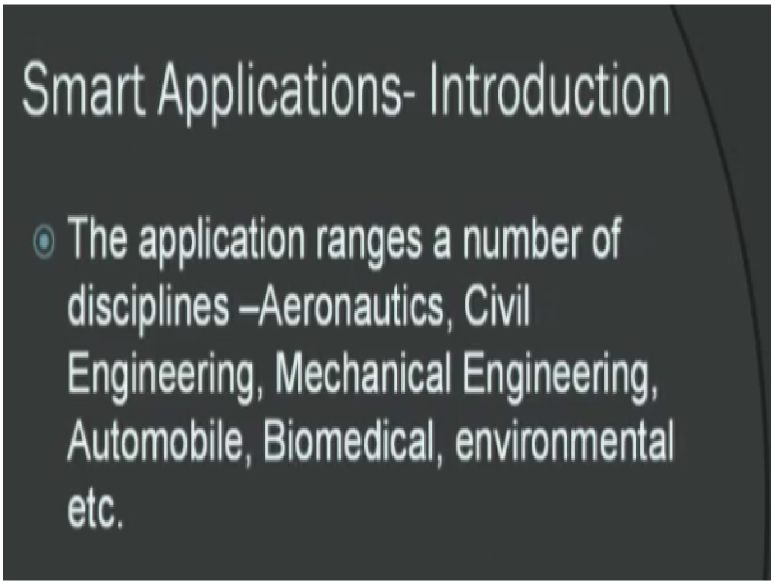

So in the lecture 2, we said that we talked about the smart materials, the principles of operations of various smart materials. And today we will see the ranges of applications that this smart materials and systems can do in the area of aeronautics, civil, mechanical engineering, automobile, biomedical etc.

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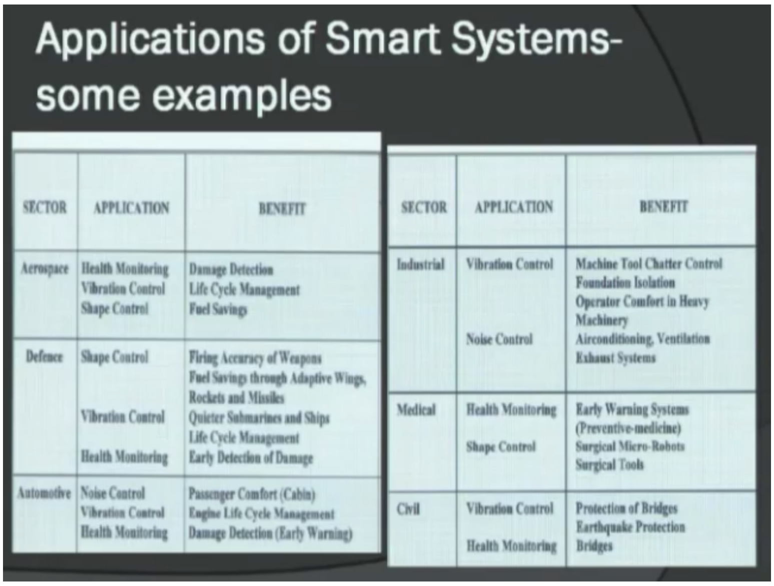

SECTOR	APPLICATION	BENEFIT
Aerospace	Health Monitoring Vibration Control Shape Control	Damage Detection Life Cycle Management Fuel Savings
Defence	Shape Control Vibration Control Health Monitoring	Firing Accuracy of Weapons Fuel Savings through Adaptive Wings, Rockets and Missiles Quieter Submarines and Ships Life Cycle Management Early Detection of Damage
Automotive	Noise Control Vibration Control Health Monitoring	Passenger Comfort (Cabin) Engine Life Cycle Management Damage Detection (Early Warning)

SECTOR	APPLICATION	BENEFIT
Industrial	Vibration Control Noise Control	Machine Tool Chatter Control Foundation Isolation Operator Comfort in Heavy Machinery Airconditioning, Ventilation Exhaust Systems
Medical	Health Monitoring Shape Control	Early Warning Systems (Preventive-medicine) Surgical Micro-Robots Surgical Tools
Civil	Vibration Control Health Monitoring	Protection of Bridges Earthquake Protection Bridges

In this very chart I brought up in the lecture 2 to see what kind of applications we can realize with smart systems and today we will go back again and then review what are the applications in various sectors that we can achieve in the smart systems. In the aerospace, we have it in the area of health monitoring, vibration control and shape control. And the major benefit is we can detect the damage, increase the life of structures, life management and also fuel savings.

In the area of defence, we require for shape control, vibration control, health monitoring again. And the benefit is firing accuracy of the weapons, fuel savings in rockets and missiles, in submarines, life cycle management etc. In automotive, the major focus is the comfort, so we require reduced noise, vibrations and also to assist the health of the structure and the major benefit is passenger comfort, engine life cycle management, damage detection etc.

In the area of industrial engineering, we require smart applications for vibration control and noise control and major benefit is to reduce the machine noise, machine chatter, and also the operation comfort of heavy machinery, air conditioning and ventilation, noise reduction etc. In the area of medicals, we require for health monitoring and shape control and some other benefits is early warning systems for many diseases, surgical, micro-robot, surgical tools etc.

In the area of civil, we require again for vibration and health monitoring and basically has increased the life of the bridges which are very old in our country, earth quake protection and also in the area of detecting damages.

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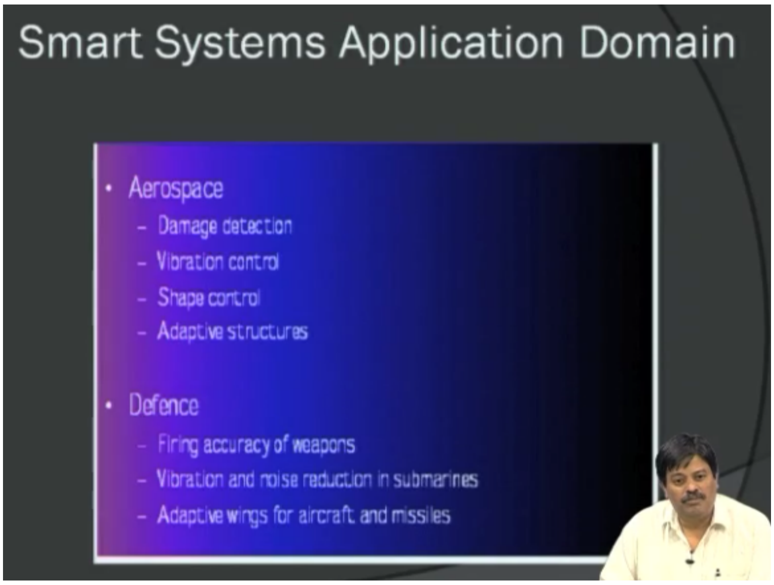

So we will now review the each one of this in more details in the area of aerospace and defence.

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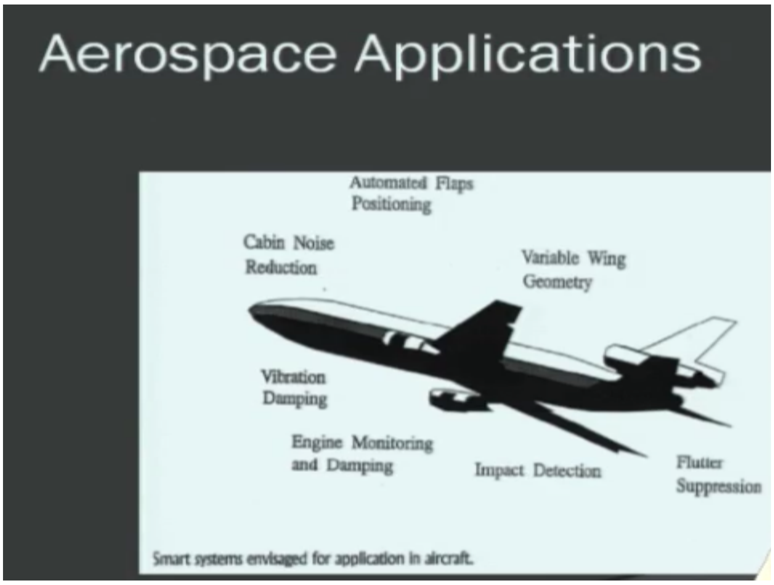

So in the area of aerospace we require smart systems for various applications such as the cabin noise reduction which is here. The cabin noise reduction which is the automated flap positioning, which is required for changing the flow of the air or the fluid in order to increase the lift. We have to have a variable wing geometry again for the same reasons. We need vibration damping to reduce damping levels in the aircraft.

We require engine monitoring because engine monitoring is very crucial to see that if any damages or anything happens to the engine it is the early warning system can be triggered. We need to detect the impact that is going to be there, so there are sensors do actually do that.

The flutter is one of the important areas in area of aerospace. The flutter causes tall reduce lift, so this has to be avoided at any cost and smart material systems can actually help do this.

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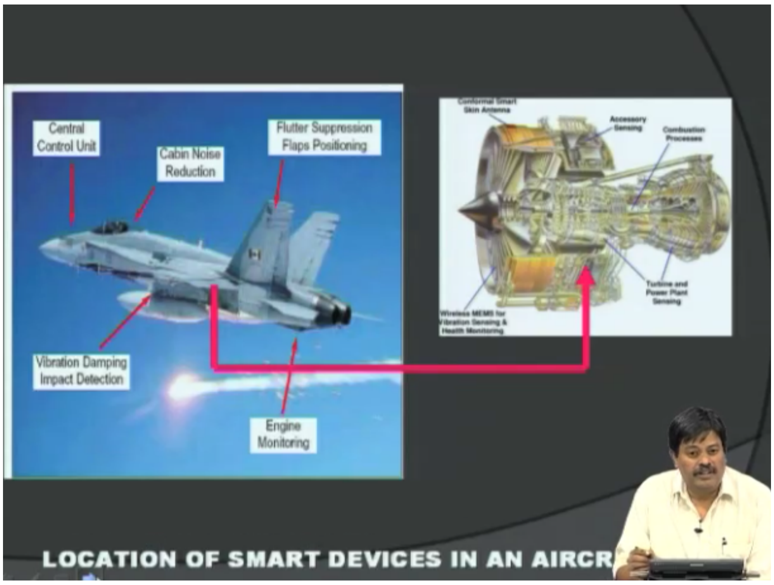

Where are these smart devices located in an aircraft. Here is the view graph that shows that. For example, we position the vibration in damping devices in the engines, which is shown here. We have the engine monitoring unit that is present here and even in the engine itself, which is shown here has very complex system, which has compressor blades, turbine blades and various other accessories bearing housing system.

So we position the wireless MEMS sensing especially in the area in the compressor blades. We also have a conformal antenna. We have other for the compression process we need some other systems. So you can see how complex the system is and the number of sensors you actually monitor is enormous. So the ranges of applications that are required for aerospace is tremendous.

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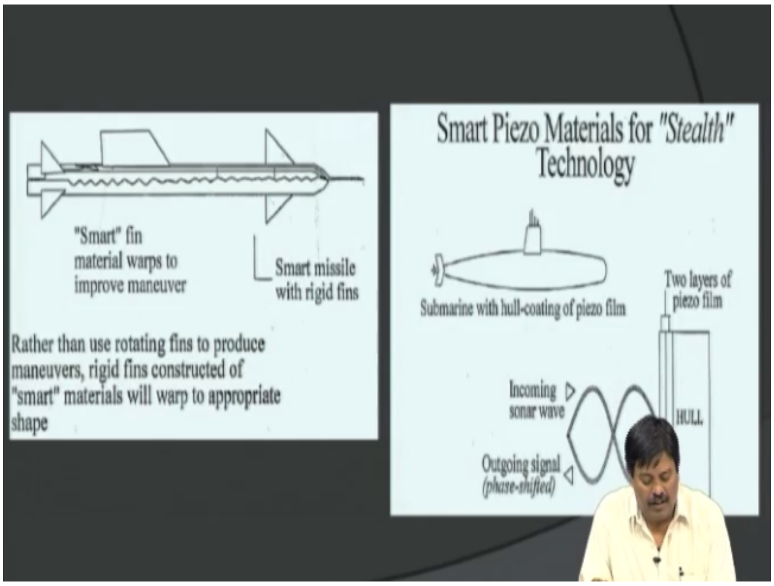

So let us move into the area of defence and one of the areas where we need a smart system is in the actually maneuvering of the missiles. Here is an example of smarts fin. You could see that in order to get required maneuver we rotate the fin. But the basic idea here is if you have a smart fin basically the smart materials can warp to appropriate shape in order to get the required maneuver. So the smart fin is extensively used in missile applications.

Another area where the smart materials are extremely use in stealth technology, especially if we use in a submarines. Here is an example here. We actually coat the ship hull with the piezo film, so the stealth is basically in order to suppress the signature that is coming L2 magnetic signature so that it cannot be detected. So basically there is an incoming wave and that needs to be either suppressed or changed in phase. The piezo can do it.

And here is an example where we can actually use piezo films in the area stealth technology.

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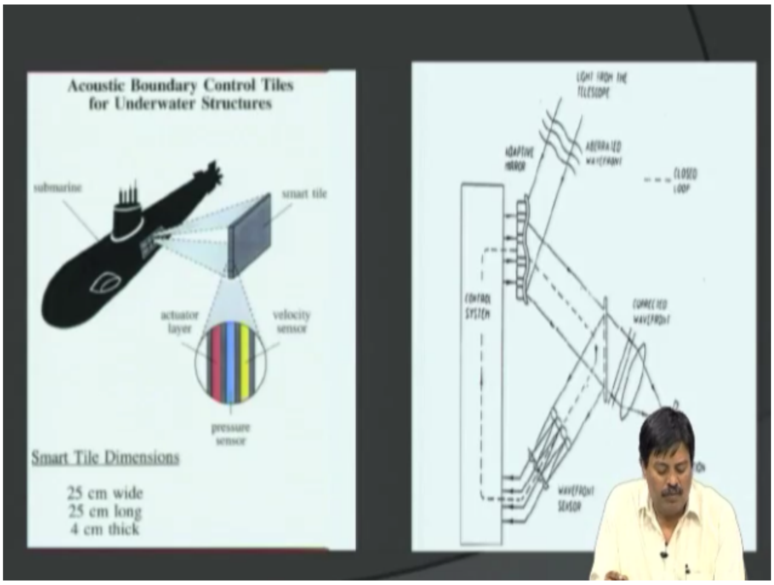

Another area is in the area of boundary control especially to see the maneuver and the flow of the submarine in the underwater structure, for which we have a smart tile and the smart tile if you see the exploded view here basically has a pressure sensor, which is going to sense the pressure and move around. There is a velocity sensors to gauge the movement of the both the submarine as well as the incoming vehicle, enemy vehicle and if the need be there is a piezo actuated that will actuate in order to stabilize the control.

So this is one area where in the area of submarines and underwater structures smart material system is very useful. Another area where we actually use in the area of telescope. So the telescope basically has a mirror and now we design an adaptive mirror in order to get a very high resolution image. So what is done here, there is a wave front sensor, which actually senses if the mirror oriented properly or not in order to get a high resolution image.

And there is a control system that is triggered, if the wave front sensor senses that the wavelength is not going to yield very high resolution images, then a control system is triggered, so that the mirror is oriented in such a way that a high resolution image can be got.

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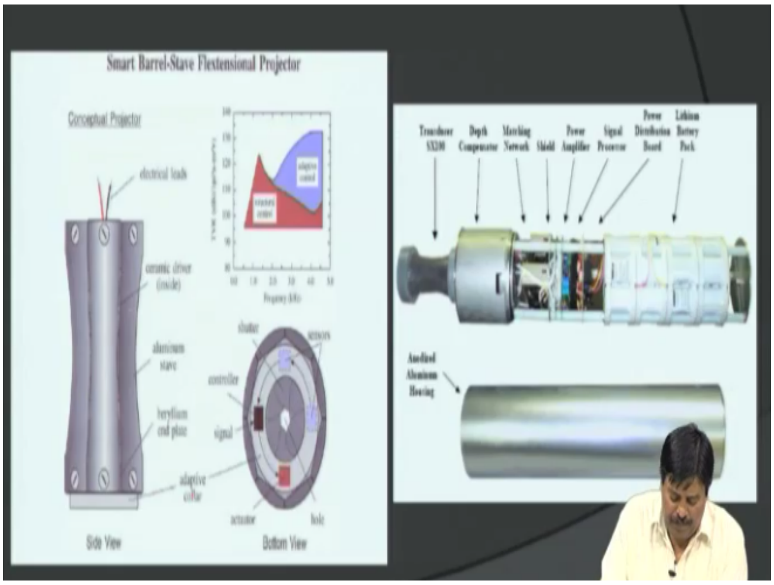

Another area where we require smart material is perfect projection of the projectile using a barrel. So here there is a smart barrel, and the smartness or the adaptiveness is related to the adaptive collar that is placed at the bottom of the barrel. This adaptive collar has to senses which actually senses the position of the barrel with respect to the target and if the target is ok, or if the target is going to be off, actuator is triggered from the control and the projectile is fired. So basically this is an adaptive smart barrel where the smart system is used.

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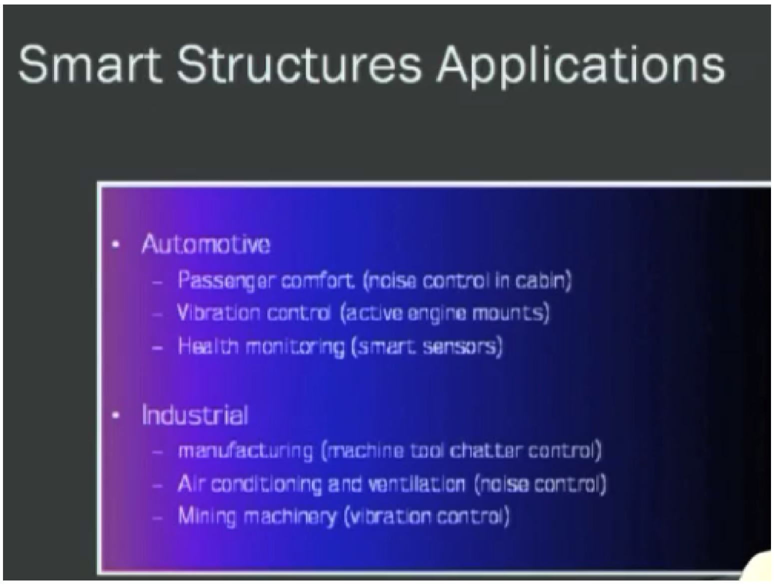

Next we will look at the area of automotive and industrial sector. As I said earlier, the major focus here is the passenger comfort by reducing vibration and also to monitor the health and in industrial the smart systems are extensively used in the machine tool, chatter control, in the air conditioning and the ventilation noise control and in the mining machinery especially in the area of vibration control.

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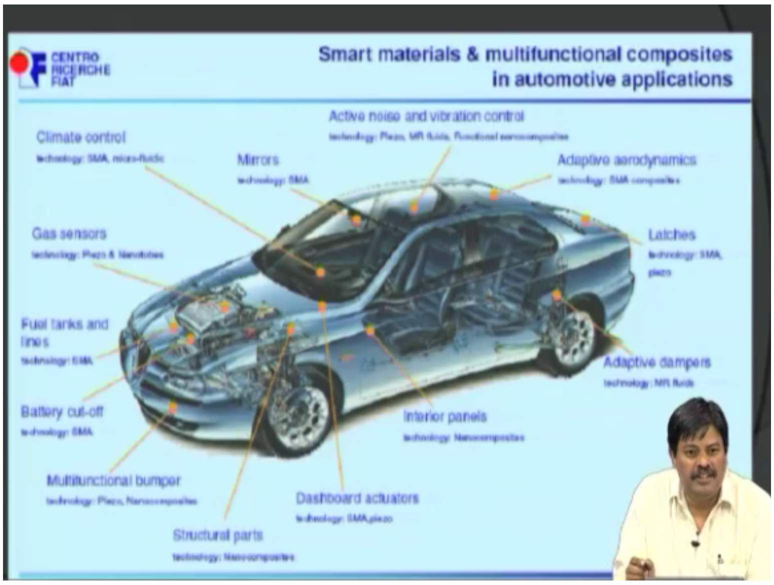

And here is a slide that has been downloaded from the internet or from the Fiat website, and this is the typical car with the range of smart systems that is instrumented in today's car. For example, the most important is the climate control and the climate control basically has a temperature sensor, which basically senses the temperature and controls the temperature, the specified temperature inside the car for passenger comfort.

The mirrors are automatically actuated using a SMA technology, basically SMA positions the mirror perfect to the driver's seat position. There is active vibration and noise control, where the piezos, MR fluid and even nano-composites are used as the basic actuators to control the vibration and noise. The aerodynamics or the flow over the car is controlled use shape memory composites.

There are latches which are smart, which are actuated by SMA. There are adaptive dampers for reduced vibration and control, typically made from MR fluids. There are interior panels which are made smart using nano-composites. The dash-board actuators are there, which are basically SMA or piezo based. The structural parts are there where they are basically it is made from nano-composites.

And there is a multifunctional bumper which basically senses the approaching target or the impact that the car is going to experience, and that is basically made of piezo or nano-composites. There are battery cut-off, if the battery has to be cut-off, then the actuator that is triggered is based on SMA. There is a fuel tank indicator that is based on SMA and piezos. So there is a range of smart sensors that today's car is instrumented for passenger comfort.

Another major sensor that is used is the gas sensor in order to control the emission with the climate change being more predominant in today's car manufacturing. So it is necessary to monitor the gas emissions from theses cars and gas sensors are extensively used which are basically piezo based or nano-composite based.

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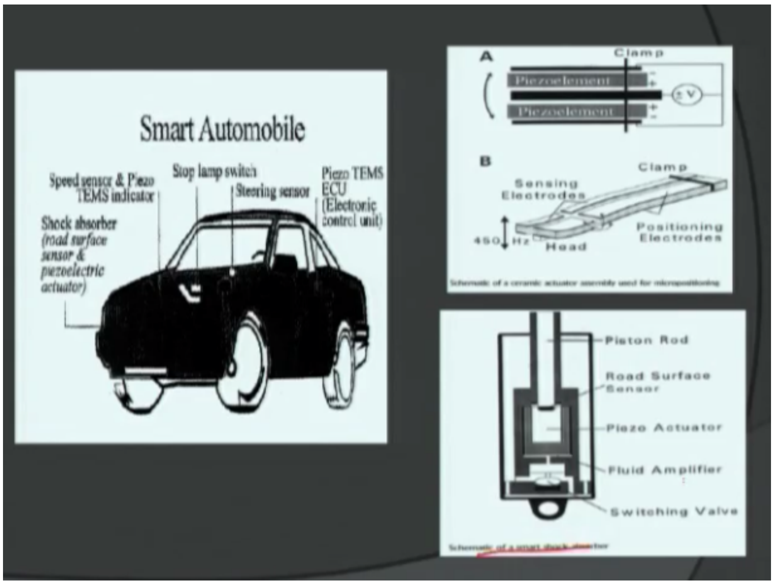

Other areas where the smart systems are used is in the smart shock absorber. If you look at it the shock absorber, you have the typical schematic of a shock absorber is shown here, which has a piezo actuator with the fluid amplifier and the road surface sensors. Whenever the sensor senses a heavy bump are some such obstructions to the car movement, immediately this smart shock absorber gets actuated in order to reduce the shock levels increasing the passenger comfort.

Other area where we have the smart sensors and the activators in automobile is in the micro positioning. So basically it has a bi-morph piezo element which is actuated, which is electroded and which is actuated in order to get the necessary positions. So there are various applications of smart systems in automobiles.

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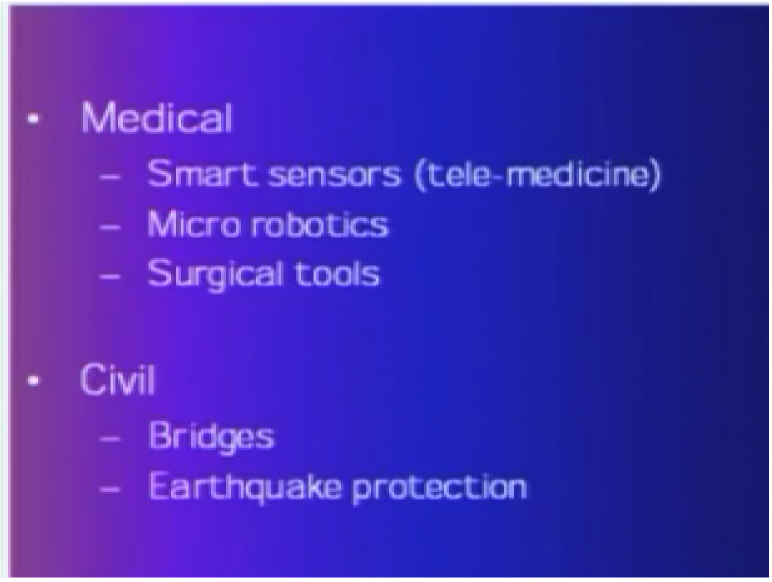

Of course smart systems extensively used in medical field especially in the area of coming up with micro-robotics, and micro surgical tools, there is a micro needles that are very famous and of course not to mention there is the blood pressure sensors for blood pressure monitor and many such applications we need smart systems. In the area of civil engineering, we need smart systems for monitoring bridges.

Many of the bridges are very old and it has to be assessed for its structural integrity, so we require structural health monitoring technique to be built into the bridges of the current and the new bridges. And we also have to look at the integrity of the structure for hazardous environments such earth quake and tsunami type of natural disasters.

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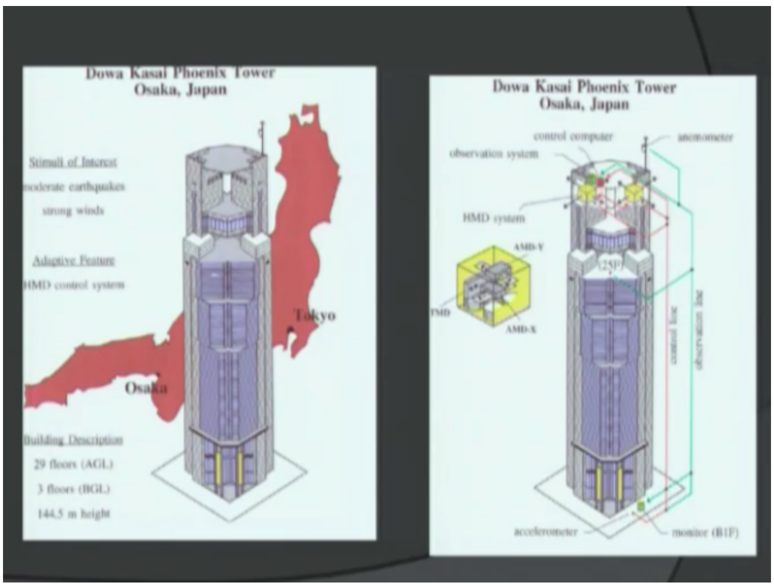

So in the area of civil engineering here is a view graph of the smart system that is built in Japan in the Osaka, Japan. And this is called the Dowa Kasai Phoenix tower which is about 29 floors. And on the right hand side one could see the instrumented smart system that is built in order to monitor the earthquakes, strong winds and any other hazardous, harsh loading conditions.

So typically the smart system has tune mass damper system which has an adaptive mass damper. In the adaptive mass damper, the mass varies based on the situations. And there is a tune mass damper which has basically function is to separate the natural frequency with the driving frequency of the wind. So the major disaster that is caused from what is known as the resonance when the frequency of the wind and the frequency of the structure coincide.

So the major function of these damper system is to actually separate out the natural frequencies of the structure with that of the loading that is coming either through the earthquakes or from the wind. So this is the typical smart system that is been built in many of the major tall rise towers in civil engineering.

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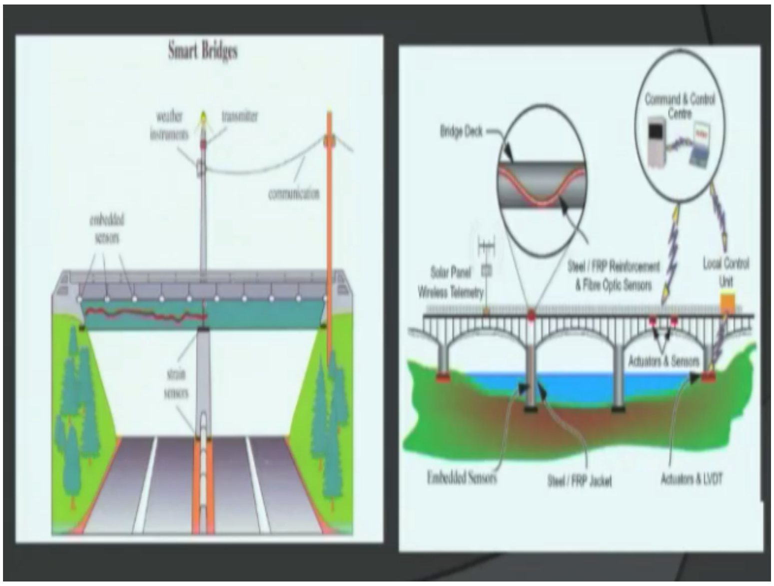

As I said earlier bridges is one area where smart sensors are used. There are two kinds of sensors that can be incorporated in bridges for constant monitoring of the strains, or the loading on the structures which can be actually post processed to find out the health of the structure. The two types of the sensors are on the left side. We see the sensors that embedded in the bridge deck as shown here.

And these are basically piezo sensors which constantly senses the strain in the structure and gives out, which can be post processed to actually find out the health of the structure. On the right, we have another bridge which is instrumented with the fibre optic sensing, and the fibre optics is very useful as opposed to, piezos from the point of view that it is immune to electromagnetic radiation and other such forces.

So basically the strains here are acquired by the fibre optic sensors through a data acquisition system, which are transmitted through an RF devices to a control room which will be far away. So basically we can incorporate the wireless sensing methodology along with fibre optics very effectively and in fact one can actually monitor the bridges at a location far away from the bridge say typically up to a kilometre away.

So today we have wireless sensors, which have a large range and a large data transfer capability.

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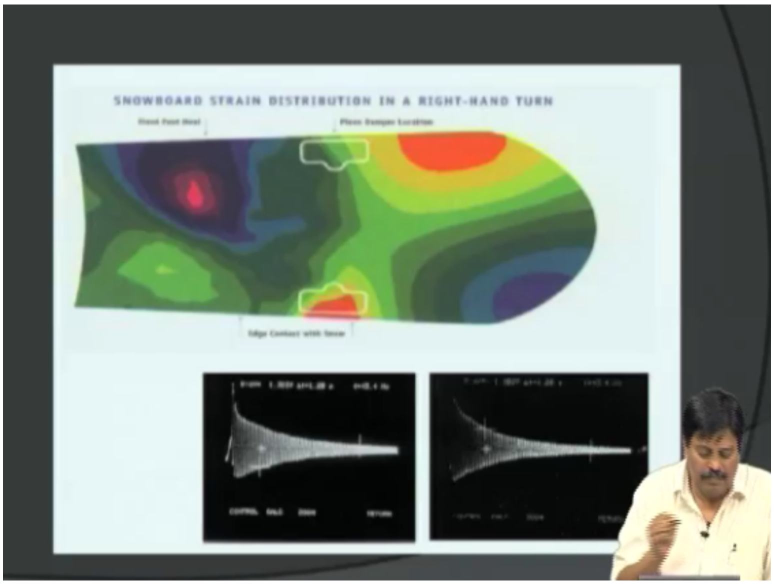

The other area where smart systems are extensively used is in the area of entertainment, where here typically there is a ski board which is instrumented with smart sensors. So basically if a person is using such a ski in order to ski, then the friction between the ski and the surface reduces to a level that the person is going to skid then the smart actuation can be actuated in order to increase the skin friction.

So there are various such applications that one can think of using smart material systems.

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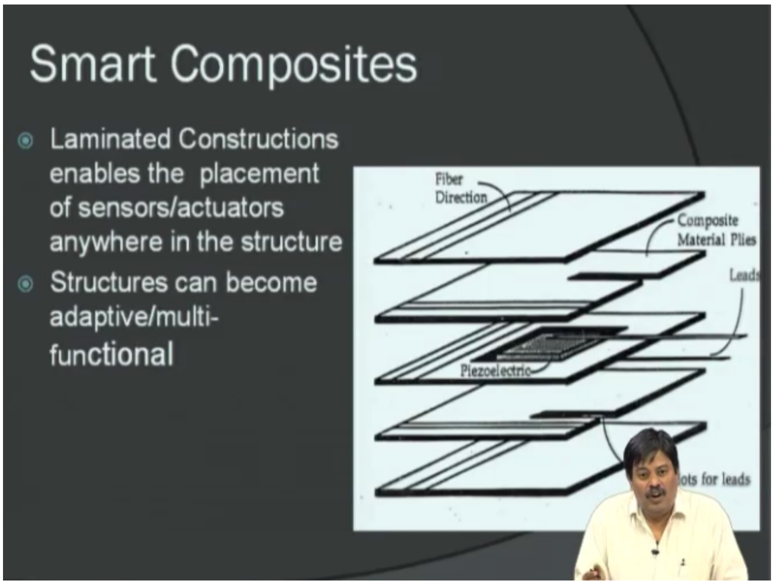

Coming back to in the area of structural engineering, today composites laminated composites are extensively used, because they are light weight and high strength. And today aerospace material is moving from the aluminium to composite because of this feature of the composites. The composite is basically made as plies and many plies are stuck together to make a structural panel.

And each ply we have fibres which are oriented in a particular direction where the strength is decide and which are held together by matrix. And these plies are queued and stuck together to make many plies so that you have a very light weight high strength material, structural material. The advantage of having a high strength, light weight is especially in structures like aerospace, one can get enhanced fuel efficiency.

This laminated construction will also have additional benefit that since it is a ply type construction, we can embed the sensor at the time of manufacturing anywhere in the decide location. Here is a typical view graph where one can actually embed a piezo sensor with the leads out and that act like a permanent sensing element that we can build in into the structure.

So that the laminated composite structure in addition to carrying loads, it can also act like a multi functional utility doing a host of other activities other than carrying load. So here is a typical case of a smart composite with a built in piezoelectric film in the laminated composite structure.

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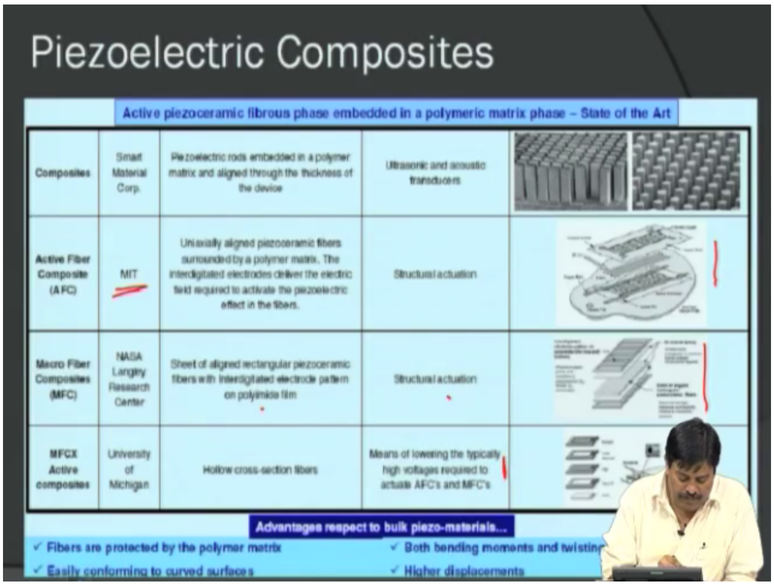

When we talk about composites, there are many variance of composites. The typical variance of the composites are the active fibre composites, which was typically made from MIT here. It is basically a uni-axially aligned piezoceramic fibres surrounded by polymer matrix. And there is an IDT which is the inter digital electrode to deliver the electric field required to actuate the piezoelectric film in the composite.

So basically it is used for a structural actuation and the typical configuration is shown here. There is also a macro fibre composite, which is basically made from NASA Langley research centre. Here a sheet of aligned rectangular piezoelectric fibres with IDT is put on a polyimide film. The difference is here it is a polymer film, it is a polyimide film. And again it is used in structural actuation a typical view of this is shown here.

There is also MFCX active composite, which is made from University of Michigan which is hollow in cross-section. So basically the other 2 require high voltage actually deliver the actuation, by making the fibres hollow, typically the voltage levels can be reduced. The advantage with respect to all these bulk piezo composites are the fibres are protected by polymer matrix, it is easily conformable to curved surface.

Both bending moments and twisting torques can be given and it can give higher displacement, that means higher control force can be generated for actuation.

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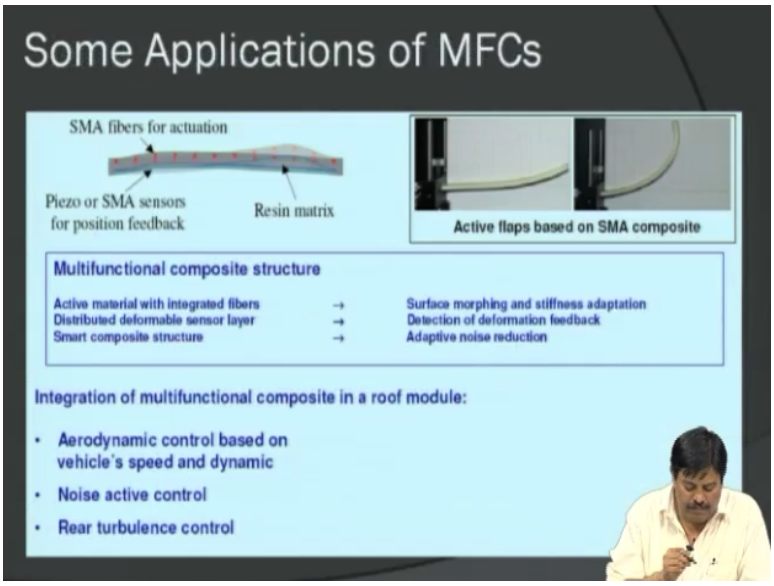

There are few other applications of MFC's that is the multi functional composites especially in the area of aerospace. For example, we require aerodynamic control. So here this is for doing the aerodynamic control, we need to change the flow across the aircraft when it is flying. And this flow can be basically changed by actually having a flap, which will basically actuate to deviate the flow from the wing section.

And here is a typical active flap made from piezoelectric and its behaviour is shown here. The other areas where we can actually use the multi functional composites, especially in aircraft is in the area of noise control and also the rear turbulence control typically by actually having this many of these flaps and flap controls.

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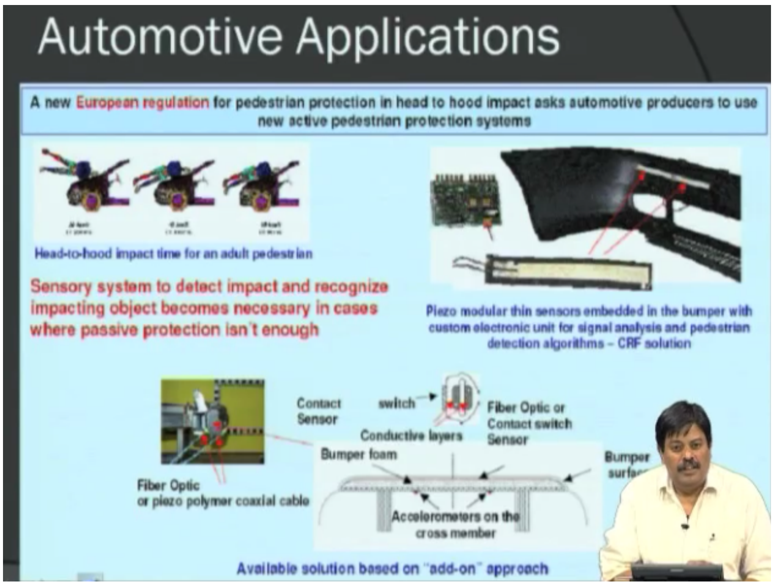

The other major applications of the smart materials is in the area of automotive applications and today in the European union there is an increased need for pedestrian protection and the automobile producer are asked to have a new active pedestrian protection system. One such system is now built into the bumper of a automobile, where there is a sensor, which is basically made of either fibre optics or the piezo based sensor.

Which basically senses the approaching pedestrian and substantially which is linked to a control system which will actuate to take the necessary steps for the automobile. This is a solution that has been adapted by the European union today to their automotive cars.

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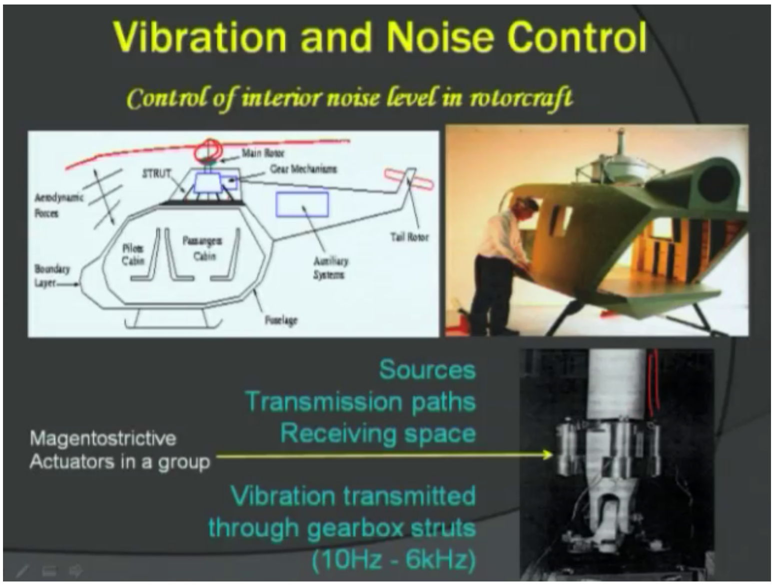

And the next area is the noise control and here is a typical application in the helicopters. The helicopter generates enormous amount of noise because of the router, which is here and this router generates enormous amount of vibration noise which are transmitted to the cabin through what are called these four struts, the active struts. So basically this struts acts as a conduit of noise and vibration from the router on to the system and because of which the cabin becomes extremely noisy and vibration levels are very high.

And the comfort of the people travelling is extremely jeopardized because of this. So there are various solutions that has been made, one such solution is to do a path treatment. So we treat the path of this strut by actually having a smart actuators so that the vibration and noise is taken away by these actuators away from the fuselage or the cabin. So here is one solution where this shows a typical strut.

And we place a group of actuators here and these actuators are controlled through a control system. So when the control system is triggered when the levels are high, this actuates gives out a control a reverse control force which takes away the vibration away from the system.

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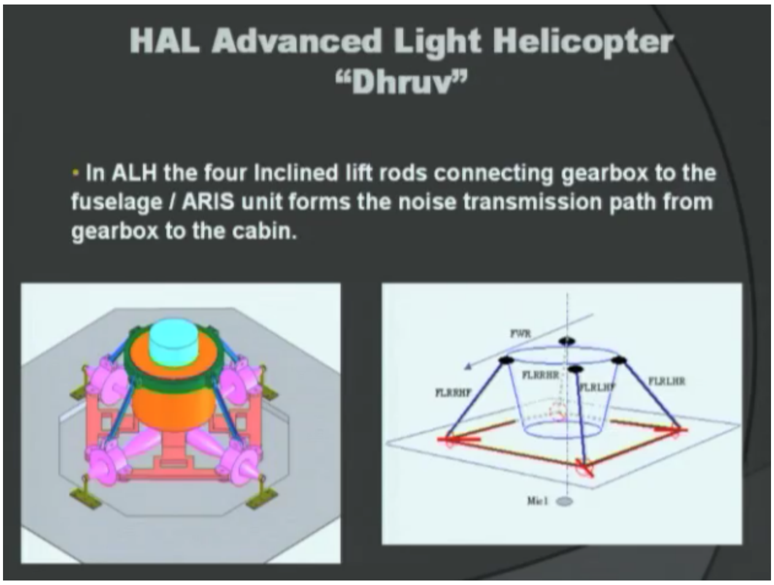

So this solution was implemented in the advances light helicopter made from Hindustan aeronautics limited. And this is a typical configuration of a smart router with the strut. These are the four struts that are present in this system.

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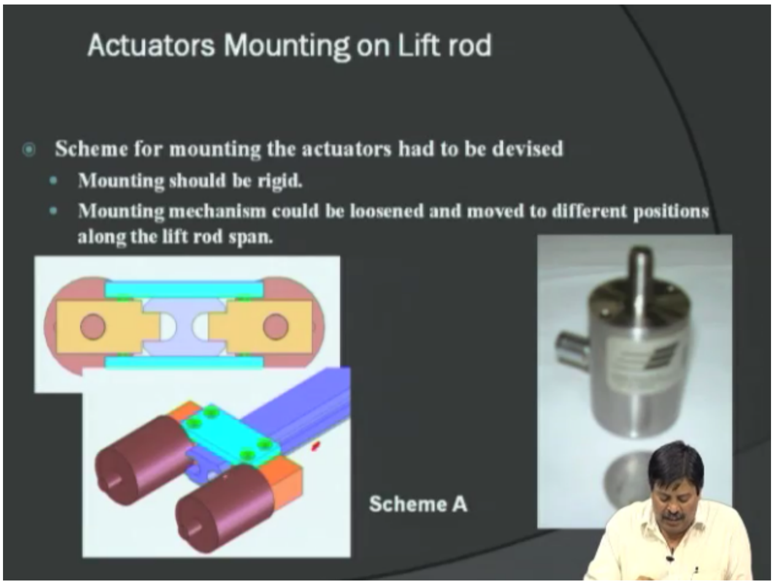

And basically a bracket was mounted and this strut was added with a two proof mass in order to give greater acceleration to the strut, so that it counteracts the forces caused by the vibration actuator, and the typical actuator used is a magneto magnetostrictive actuator. The schematic of this is shown here. It is a package actuator which can deliver up to 500 to 1000 Newtons of force can be generated with this kind of an actuator.

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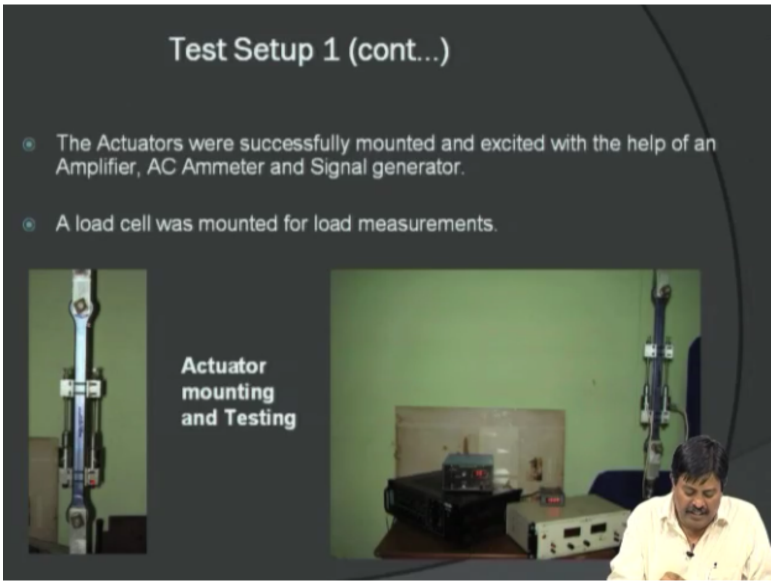

The actuator was loaded here with the bracket here and this is the strut and the experiments were performed in the laboratory and the load cell was mounted for the load measurements in order to find out the levels of the load coming here.

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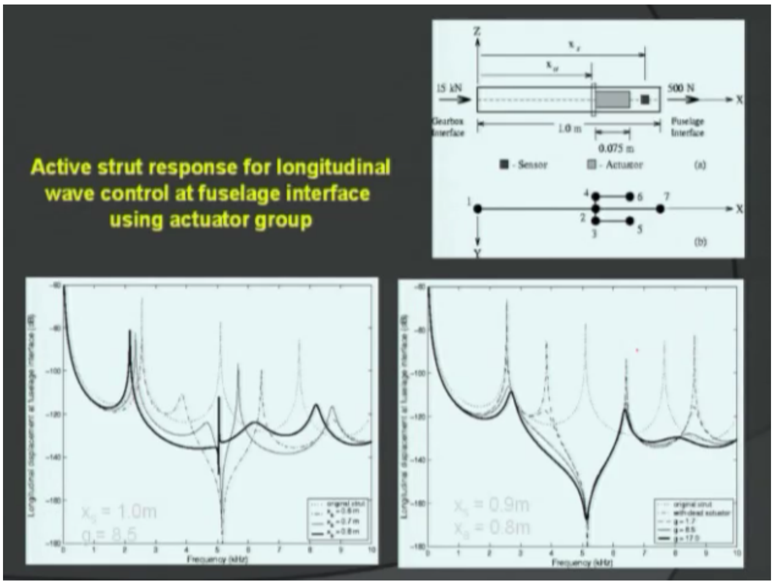

And this is a theoretical model, which was developed based on spectral finite element formulation. One could see that when the control gains are increased, the right hand view shows the three sets of curves, one that the original strut how does the vibration levels are changing, one with the group actuated introduced, so basically the vibration level shifts a little bit and when the control system is triggered.

One could see with the control gain of close to 17, practically all the modes which are crossing heavy noise and vibration is suppressed. So this is basically was done in a theoretical frame work.

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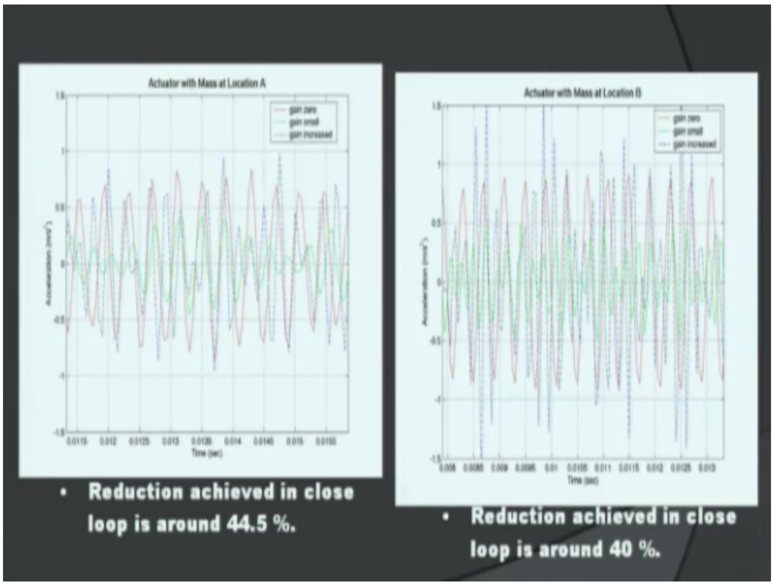

And this was later checked with the experiments. So in the experiments we could see the two levels at the two locations, location A and location B, one could see that one could attain a noise level reduction of about 45% in one location and 40% in the other location. So basically by doing the noise treatment using magnetostrictive actuators, you can reduce the interior cabin noise to the level of 45 to 50% in a helicopter which is a huge reduction.

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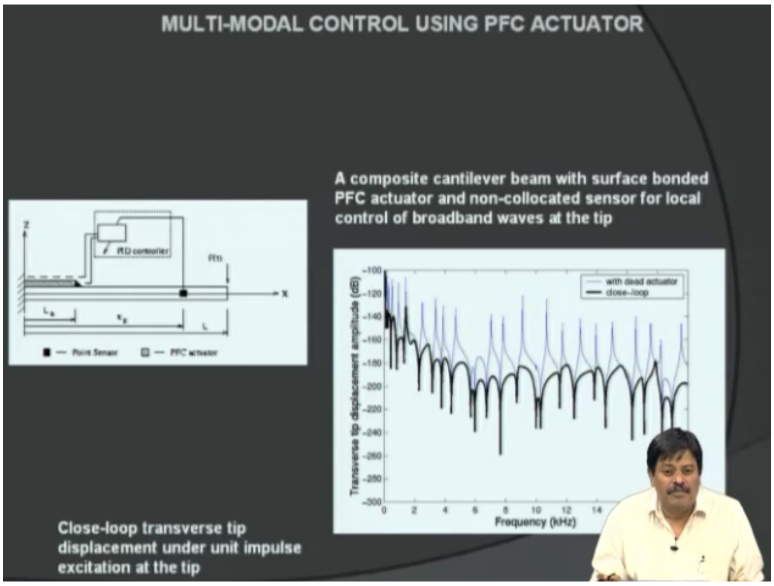

The other area where we can actually use the control system and control the many modes coming is using the piezo fibre composites, which I talked about earlier to control the vibration levels in a structure. Here there is a typical cantilever beam with the piezo fibre composite present here at the root, the reason why it is put in a root is because the stress levels are very high there.

And second thing it is subjected to a very short term burst which is triggers many modes to participate in the motion. That is, it is not a single mode problem, vibration problem, it is a multi mode vibration problem. And it is necessary to control as many modes as possible for the sake of increasing the structural integrity of the structure. So in this cantilever beam, such as a short bust mode as short as 50 micro second was triggered.

And you could see that the blue lines here are the responses that are due to this short bust without the actuators. So the moment the actuator is made active that is, a closed loop control was triggered using just a PID controller you could see that most of the modes are suppressed. So this is one of the crucial things that a smart actuator can do for reducing the vibration levels.

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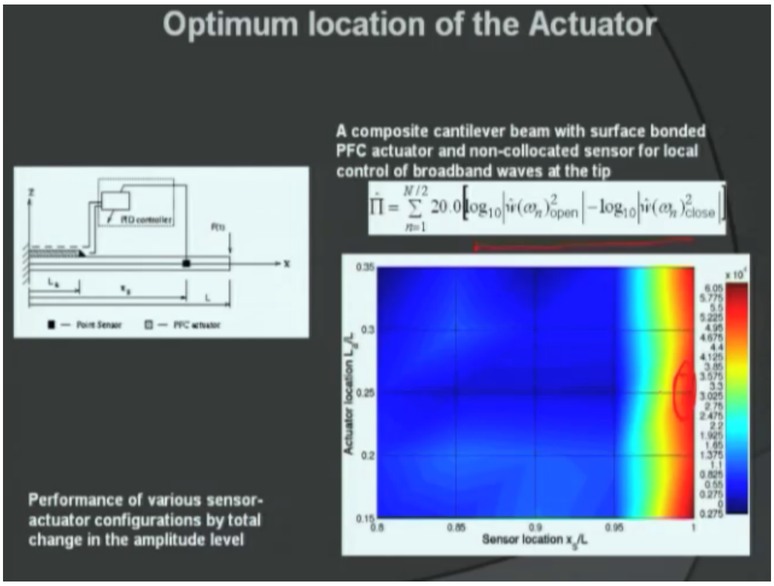

The other where we could actually do this in the same structure we need to know where we should actually place our actuator, where we should actually place our sensor, because in most of the actuation and control the actuator will be triggered with the sensors sends signal to the controller. So the position of the sensor for controlling the PID control is very crucial for the suppression of the vibration levels.

And here is a plot of the sensor location was its actuation location and what is plotted is the level of the response, which is quantified by this expression, which is basically based on the out-of-plane displacement of the open loop and the outer plane displacement of the closed loop. So we clearly see around this location is the best location for basically placing the sensor for getting the maximum sensitivity for your actuation.

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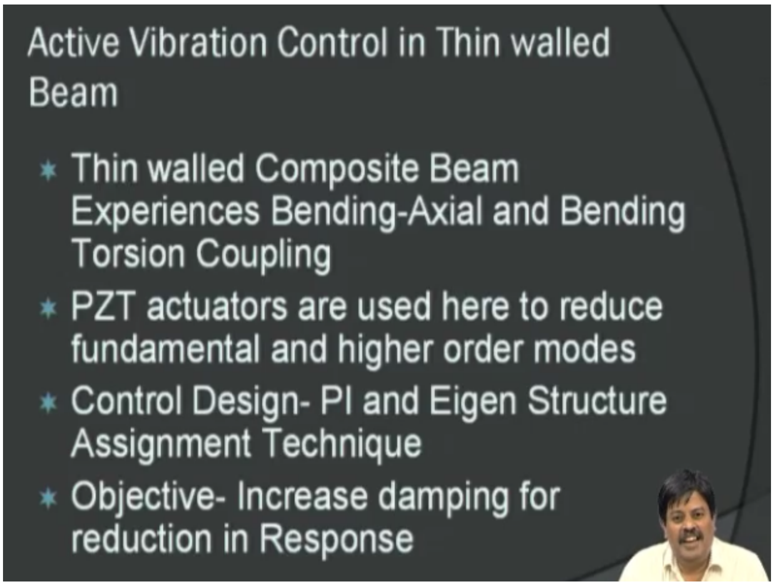

Next we will see another case study where we can actually an active vibration control in a thin walled beam. Thin walled beam are extensively used in aircrafts construction, because the prime objective is to reduce weight of the structure for increasing fuel efficiency. The reduction of the skin thickness will cause the secondary effects, such as the warping and the bending axial and the bending torsion coupling.

So here what we are trying to see is the, and because by reducing the thickness of the members the mass reduces and the vibration levels can also increase. So here what we have used is we have used PZT actuators to reduce fundamental and the higher order vibration modes. And the control design we have taken, instead in PI we have actually used the Eigen structure assignment technique to actually see whether we can actually reduce the control.

And the major objective here is to increase the damping level by doing so we can actually reduce the response.

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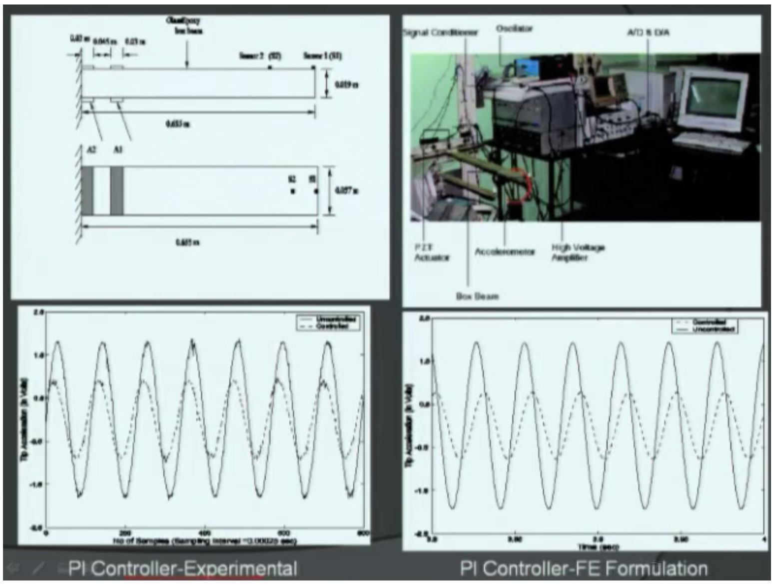

So here is a case of a cantilever beam where the PZT actuators are mounted both on the top and the bottom surface of the beam, and this is the side view. And this is an experimental set up where there is a beam here and the PZT is actuated using a signal generator which is connected to an oscilloscope and the data acquisition system. So the left side, this is the response of the beam.

The tip response of the beam due to that obtained from the experiments, and the tip response of the beam obtained from finite element formulation. We will talk about finite element formulation a little later. So we could see that both the experimental and the theoretical predictions are very good. And you could close to about 40 to 50% reduction in the response here. The dart line is the uncontrolled response and the dotted line is the controlled response.

And the control was given through a simple sinusoidal input. So we could see that the PZT actuators certainly are able to reduce the vibration levels in a structure.

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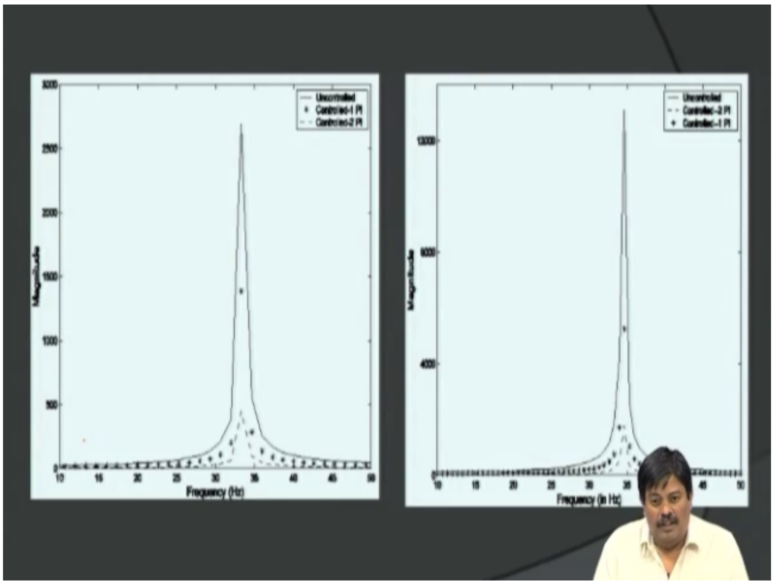

The previous plots are basically based on the time domain. Now in order to look at the frequency domain, because what we have given is a simple sinusoidal input triggered at certain frequency. So the frequency response will also have a peak in the frequency where we triggered and that is clearly seen here. So the basic objective here is by using the PZT actuator are we able to control, see the reduction in response both in time and domain.

In the previous curve, we saw there was a reduction in the responses in the time domain, and now we can see that in the frequency domain we see one predominant mode triggered at about 32 kilohertz and we could see that the frequency amplitude decreases with the control. And more over there is two curves here, one based on only when you had one set of PZT actuators and one when you have two sets of PZT actuators.

We see that having more set of PZT actuators, the reduction levels is got from here to here and here even this. So basically by using more PZT actuators we can generate enormous amount of control force which can reduce the vibration levels. And the right hand side here is when the input levels are very high. So even with the input levels are very high the vibration levels are very high, because the input level is a higher magnitude.

But still the control is very operational and the PZT actuators are able to do the control very well and this was correlated both from the theoretical studies and also the experimental studies.

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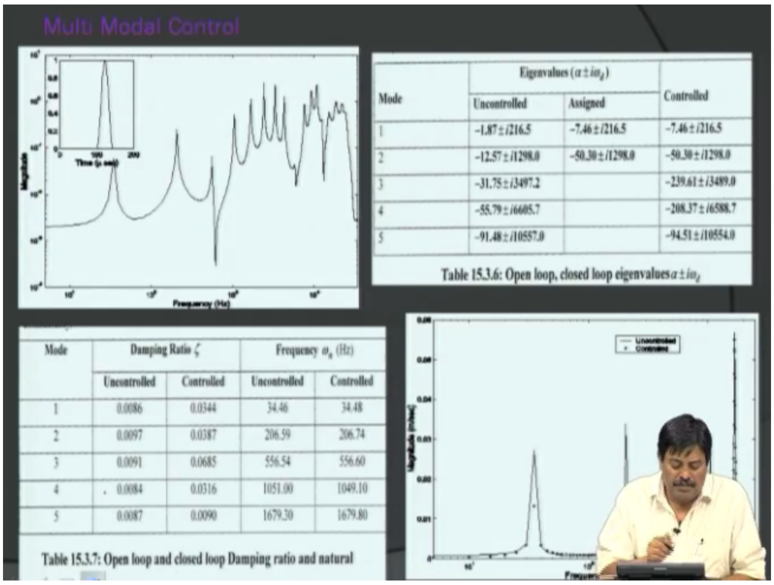

The same examples were triggered with the short bust pulse, which is just about 50 micro-second duration here. When you take the frequency response functions you could see that it triggers may modes. All these spectral peaks correspond to the modes that these short bust pulse is triggering. So our objective here is it is not sufficient we control the first mode alone, we need to control all these modes as possible, that is the major idea.

So we actually introduce the control system and we calculated the damping levels and when you look at the damping levels the uncontrolled has very small damping, whereas by introducing a control from 0086 we have made 0344. And even though we targeted only 2 modes to control that is first and second we could get on the right hand side we could see, we could get almost 4 modes to control.

So this is a very effective methodology that we have adapted the control system along with the PZT is able to actually even reduce, suppress the vibration caused by the multi mode phenomena caused by the short bust force.

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The next important area what we are talking about is the structural health monitoring. Till now what we saw is most area were dwelling in the area of vibration control, noise control, the flow control and those kind of applications. The structural health monitoring is basically assessing the health of the structure. It is similar to a structural doctor, I would call.

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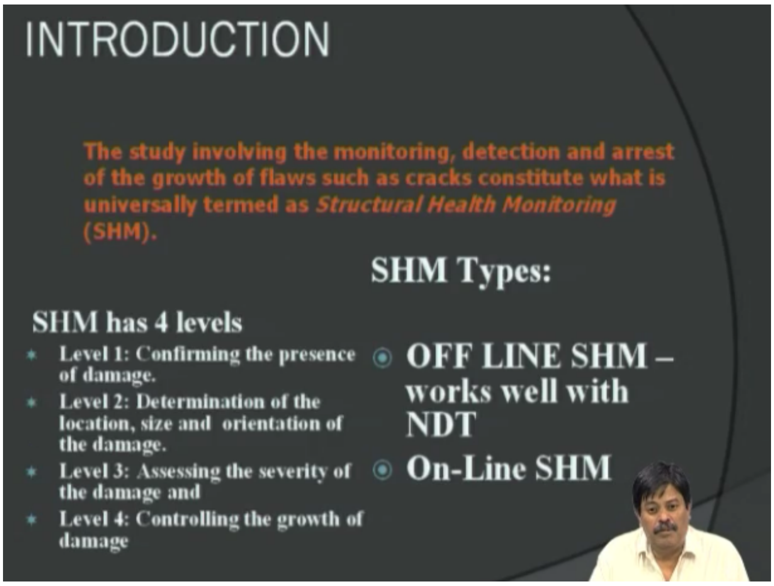

So what is structural health monitoring, it is a study involving the monitoring, detection and arrest the growth of flaws such as cracks constitute what is universally termed as structural health monitoring or SHM for short. And the SHM has 4 levels, first is just to say whether the structure has any damage or not. The next level is once you know there is a damage then where is the damage located, what is its size, extent, now what is the orientation of the damage.

And the level 3 is after determining the location of the damage, we want to know how severe the damage is, is the damage is going to grow or not, or it is going to be stagnant. If it grows it is going to be catastrophic. It is going to actually lead to the failure of the structure. And the level 4 is, if there is a damage that is as potential to grow can we control the growth of those crack or damage.

So these are 4 four levels and each level is in order of magnitude complex than the others, when we come from 1 to 4. And the SHM types can be offline of online. So offline is once a system like a aircraft can down to the hanger and then we do the SHM studies to find out the whether the damage is there. Online is as the aircraft is flying at the onset of damage it has to be known to the people who are driving this system that is the aircraft.

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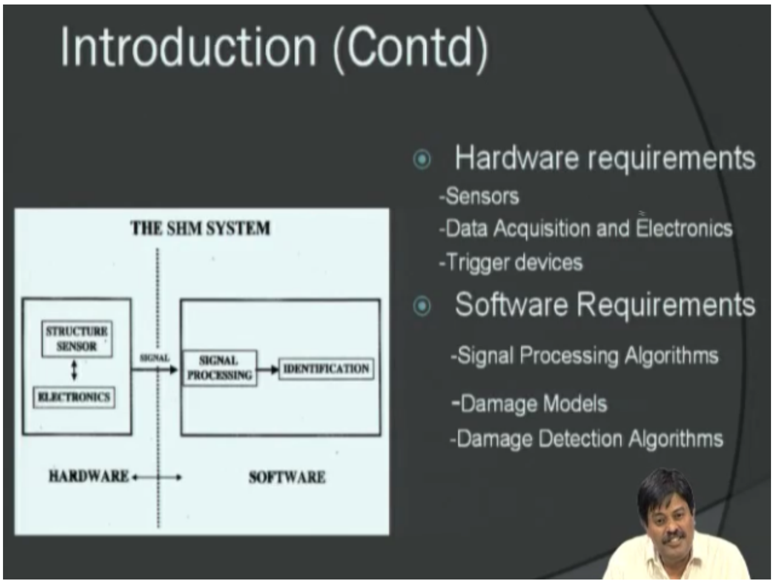

So SHM system basically has hardware and software. The hardware components are basically the structures and the electronics and the software component is basically the signal processing and the identification. So the hardware requirements are basically we need sensors different kinds of sensors, smart sensors, actuators, data acquisitions, electronics and also trigger devices to actually trigger the required inputs.

And the software requirements are basically the signal processing algorithm, the damage modules, we need to actually build based on mechanics and the damage detection algorithm based on various tools such as the mechanics based damage detection algorithm, or the soft computing tools like the genetic algorithms or neural networks, etc.

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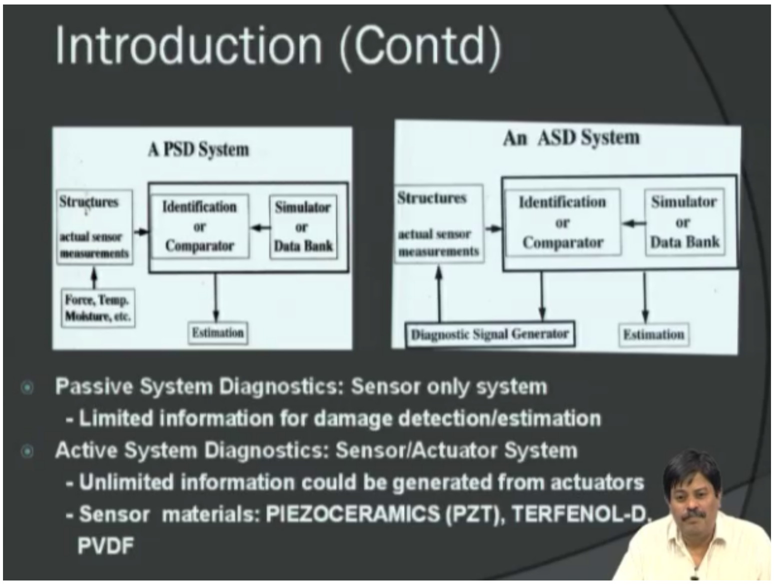

So a detection system can be passive or active, so in the passive system you input a force, whose magnitude and the time profile you do not know and you find out, you measure the strains using conventional strain gauges and from based on those data you should find out where the damage is taking place. So in short, in passive diagnosis system, it is a limited informative system, you do not have plenty of information because it is sensor only system.

As opposed to this, if you take an active diagnosis system the sensor which you are using can also actuate. So basically you can trigger a pre-determined input force, whose profile you know and you have the same system can actually measure the output in the form of strains or velocities or accelerations, etc., and hence there is a plenty of information unlimited information that you can have to actually detect the damages.

So there are various materials, sensor materials that are there, those are piezoceramic, Terfenol, PVDF, that is polyvinyl difluoride. These are some of the materials that can be used to actually use as the sensor actuator combination materials.

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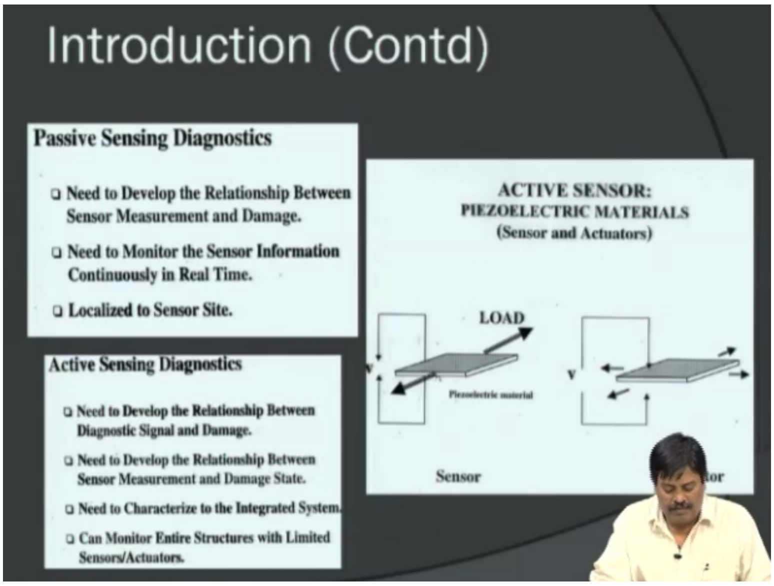

And the typical load, we always use piezoelectric actuators to trigger the load and the operations we discussed in the lecture 2.

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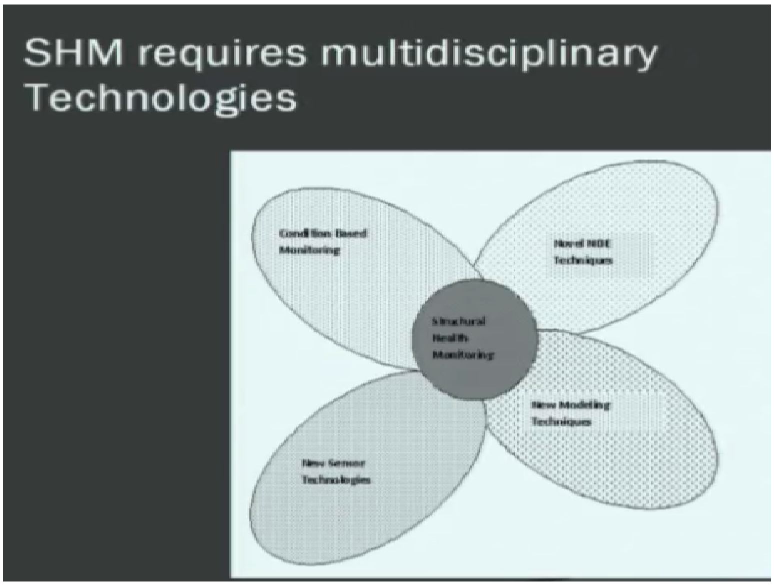

The SHM is a vast area which requires a multi disciplinary technology understanding. So it basically comprises of 4 major sub-divisions, where we need technologies understanding. One is the condition based monitoring, we need new NDE technologies, we need new sensor technologies in order to get that and most important is new modelling techniques, without modelling in order to find out where the crack or a damage is there becomes extremely difficult.

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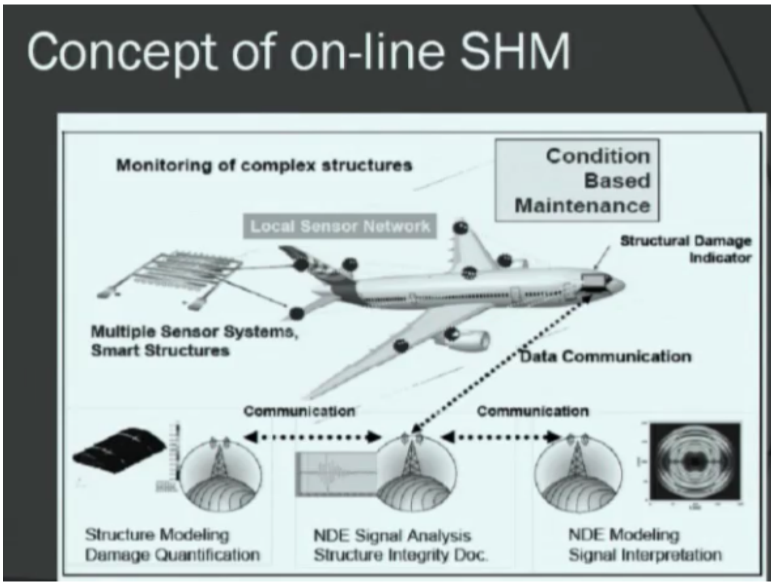

So typically we are looking at a typical system say for an aircraft, the aircraft will be basically instrumented with unlimited sensor network, multiple sensor systems and these basically will actually acquire the data, analyse the data and the data is sent back to the control room through a data communication, and this is analysed using the NDE and the structural modelling tools and immediately if there is any alarm that needs to be sounded it is sent back through an advanced communication system.

And this is what we call an online health monitoring that required, which requires understanding of new NDE technologies, new modelling methods, damage detection algorithms and advanced communication technologies in order to do that.

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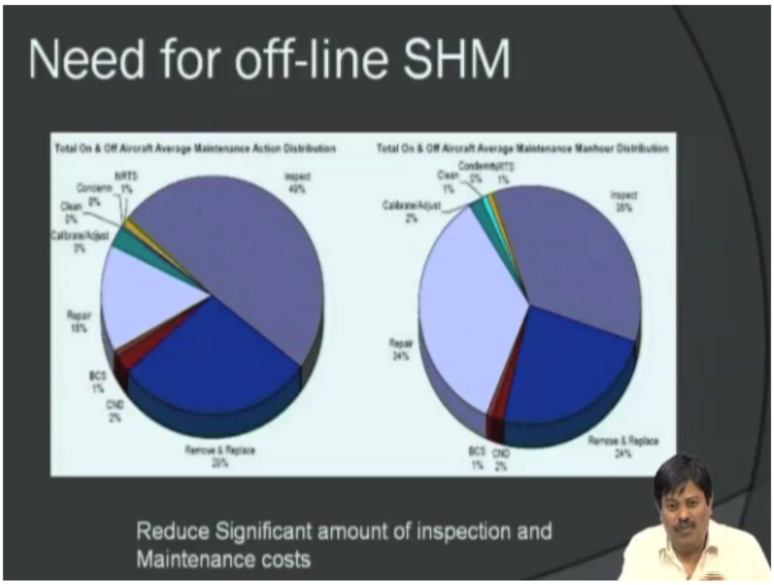

And when come to offline health monitoring, if you take a typical aircraft, there are various activities one has to do, one is the inspection, one is the repairing, the other is the miscellaneous activities, there are plenty of things. So if you look at this, the inspection amounts to about 40% of the total maintenance cost. And every time an aircraft flies after a certain number of hours, they are retired to the hanger and each part is removed and it is put through thorough NDE inspection to find out where the damage is.

If we can reduce this by building the smart system in it and that takes just a fraction of few hours, in order to assess it compared to many days that are currently being taken. We can significantly reduce the offline health monitoring cost. And this is one of the goals of the health monitoring. So if you build in the health monitoring process into the system, we can significantly reduce the offline health monitoring cost.

That means reduce maintenance cost that means the reduce time means that much hour of reduced time is available for flying to many of the aircraft companies, which is very crucial today.

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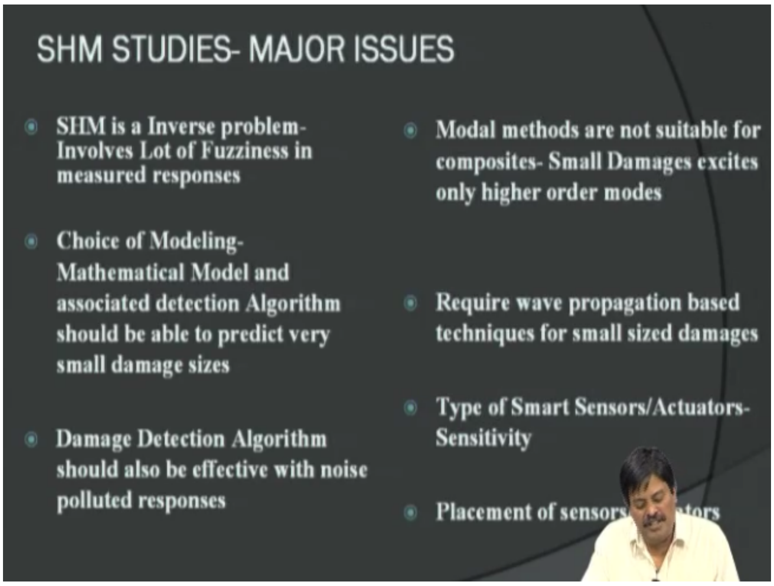

So there are various problems, major issues, lots of fuzziness in the health monitoring from the measured response and what is the type of modelling methods we need to use, what kind of damage detection algorithm we have to use, because most of the measured response is either noise polluted or incomplete and we have to detect based on these methods.

And where do we have, what type of sensors we have to use for this, that has better sensitivity or actuation authority where do you have to place the sensor. These are major issues that are involved in the structural health monitoring.

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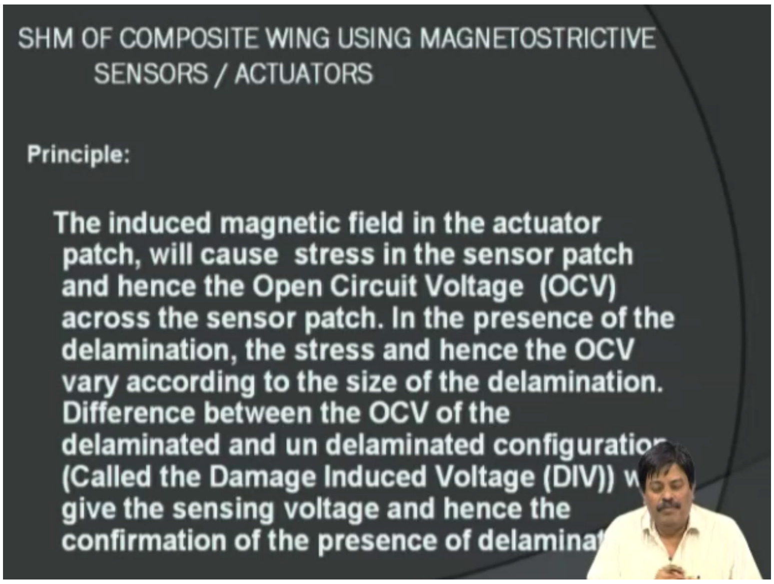

So here are some case studies, and here basically we have actually used the magnetostrictive sensor to actually detect the presence of damage that is the level 1 damage. So basically what we do have we have a magnetostrictive material basically which is used like a horse-shoe type magnet arrangement which is attached to the structure so one leg of the horse-shoe magnet will act like a sensor, other will like actuator.

So when there is a change in stress the open circuit voltage across the sensor changes by measuring the change of the open circuit voltage before and after the damage has taken place, we can actually confirm the presence of damage.

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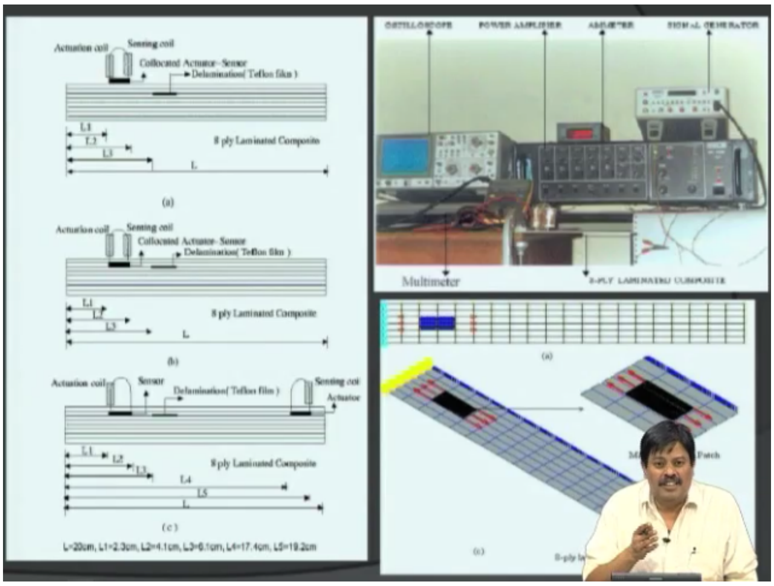

The concept is schematically shown here. So this is the horse-shoe type magnet that is attached to a laminated composite and one leg act as a sensor, other leg acts like actuator and the damage is present here. So the presence of damage will alter the state of stress which will change the voltage. By measuring the voltage constantly, we could actually know whether the damage has taken place or not.

And such a study was done both experimental and theoretical and the experimental study is shown here. The horse-shoe type magnet arrangement is shown here, where the 2 coils are there. This is the 8-ply unidirectional laminate that is used and the signal is triggered a current is passed, magnetostrictive material works on the principle of magnetic field which is created based on the current.

So this is passed here and we can actually amplify the voltage and acquire the data. So these are basically passed here.

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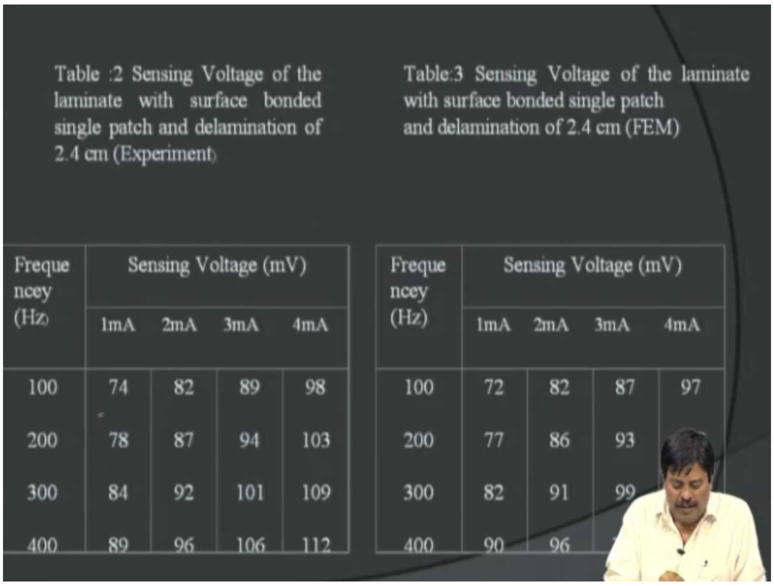

Table :2 Sensing Voltage of the laminate with surface bonded single patch and delamination of 2.4 cm (Experiment)

Frequency (Hz)	Sensing Voltage (mV)			
	1mA	2mA	3mA	4mA
100	74	82	89	98
200	78	87	94	103
300	84	92	101	109
400	89	96	106	112

Table:3 Sensing Voltage of the laminate with surface bonded single patch and delamination of 2.4 cm (FEM)

Frequency (Hz)	Sensing Voltage (mV)			
	1mA	2mA	3mA	4mA
100	72	82	87	97
200	77	86	93	[illegible]
300	82	91	99	[illegible]
400	90	96	[illegible]	[illegible]

We could see, the current as a function of frequency and the amplitude and this is the experimental one, this is the theoretical one for a 2.4 centimetre delamination on a 20 centimetre long beam. We could see that the sensing voltage is of the order of millivolts, which can be easily captured and read from our device and there is a good correlation between the experimental and theoretical.

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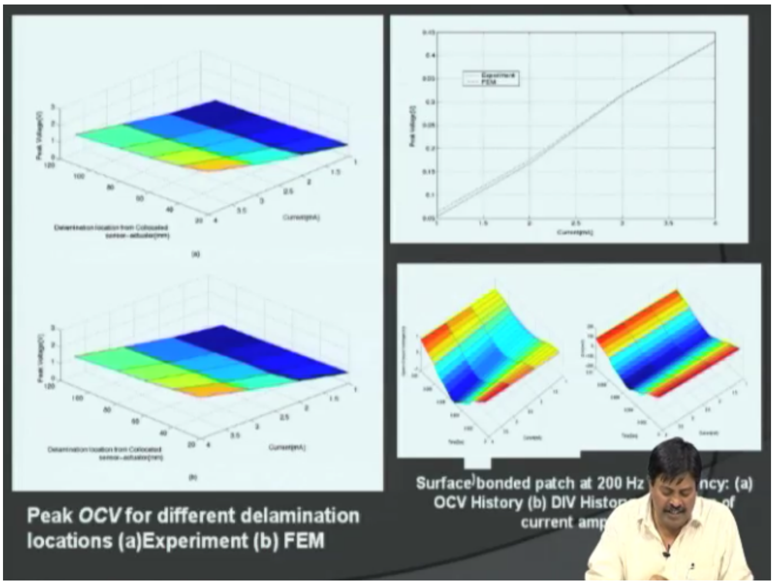

So these are the some of the things, how this whole thing varies.

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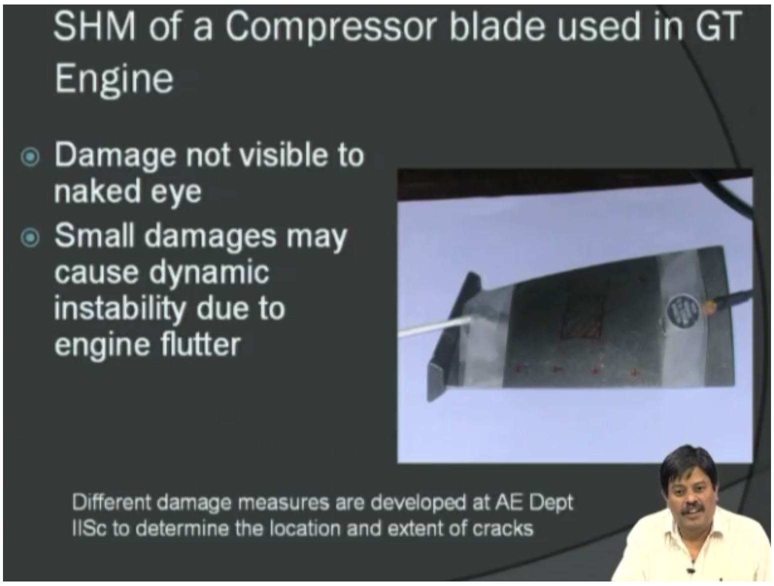

The other one is we have used this, the turban blade which is an essential component of an engine, and here they stresses, because this will be rotating close to about 12000 to 15000 RPM. And based on this the stress levels are going to be very high in this region and which is going to cause lots of the damage is going to initiate somewhere in this region. And this is basically made from titanium.

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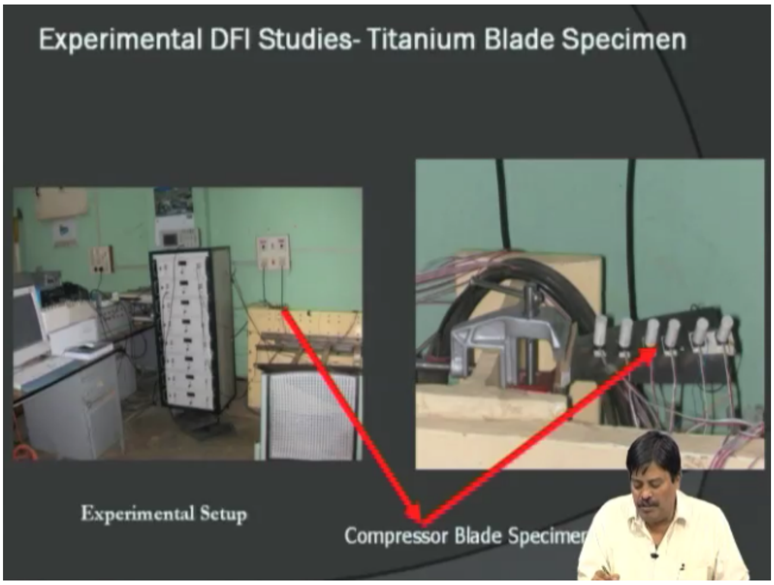

And here what we did is we mounted 4 piezo sensors, 4 accelerometers in order to measure the accelerometers and the signal was triggered here, and in order to find where the damage is.

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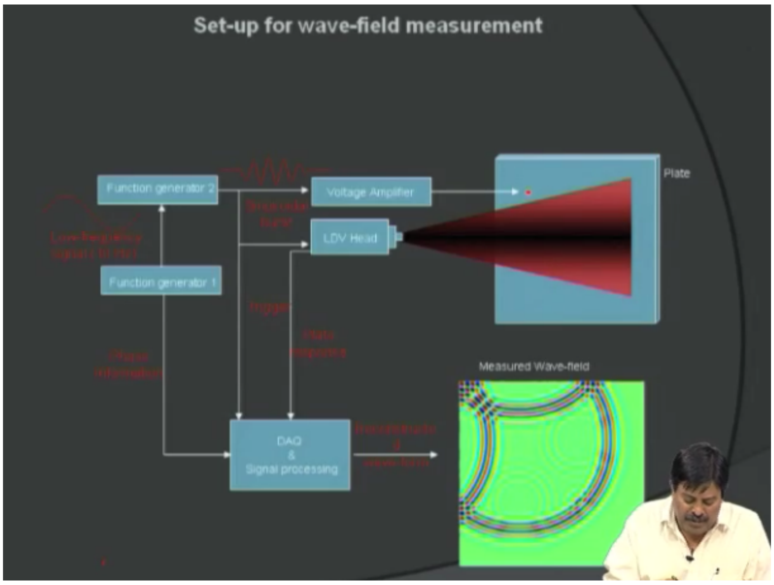

And we plotted what is called the damage force indicator as a method to actually do that, and when we do that we could see that this value of the damage force is exactly peaks in the location of the damage. And this damage is of 20, 25 micron size not visible to naked eye and this good modelling tool and very good sensing capability of this sensor we would be in a position to actually locate such small damages and the damage size is shown here, it is a very small damage of the compressor blade.

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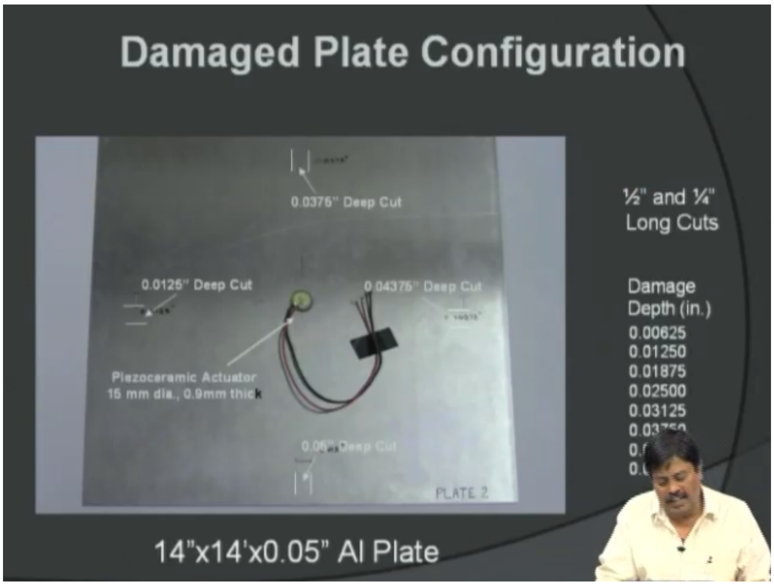

The other area where now it is rapidly going is in the area of health monitoring. I mean using the non-contact sensing, using the laser vibrometer, where we get the complete wave field here and this is a non-contact measurement where you have a low frequency device which is triggered, which is amplified to a high frequency region, and there is a laser beam that is thrown here when the structure vibrates it acquires the data, the complete wave field.

And this has a plenty of opportunities for health monitoring.

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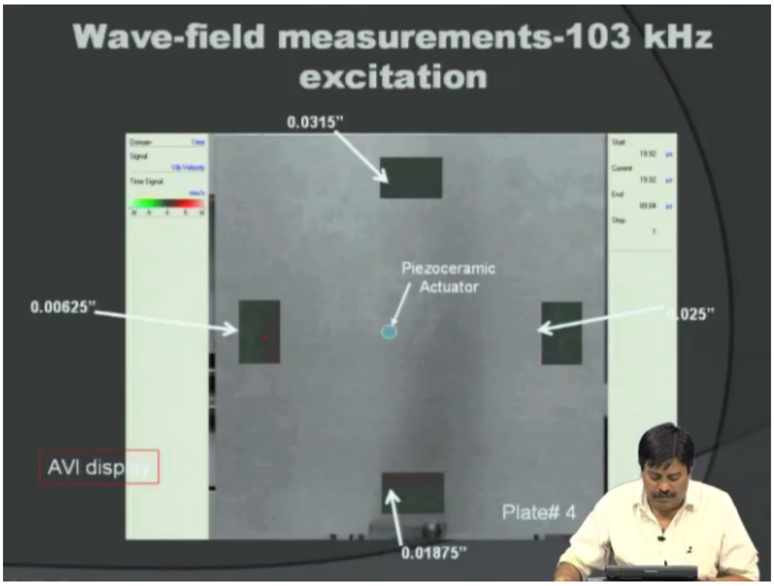

Here is a plate of 4 different damages and these 4 regions can be separately monitored using laser vibrometer which has different cuts. So basically we will get different amplitude of the damage index that we are going to plot here.

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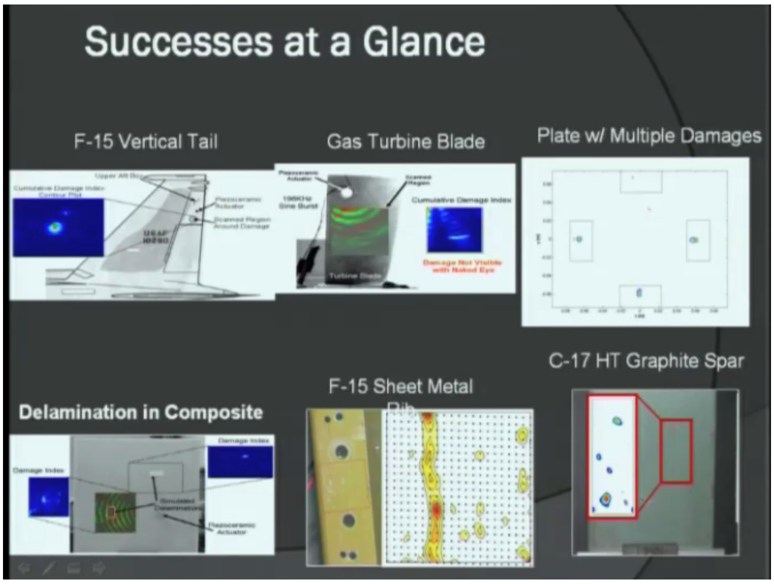

So we could see that, the wave field moving in each of this area captured by the laser vibrometer and we could see something like a completely mode conversion taking place indicating the presence of damage using this non-contact sensing. And this is very useful ideal for offline health monitoring if you have this laser device in an aircraft hanger and it will be possible to monitor the small damages and this is a way now things are going for.

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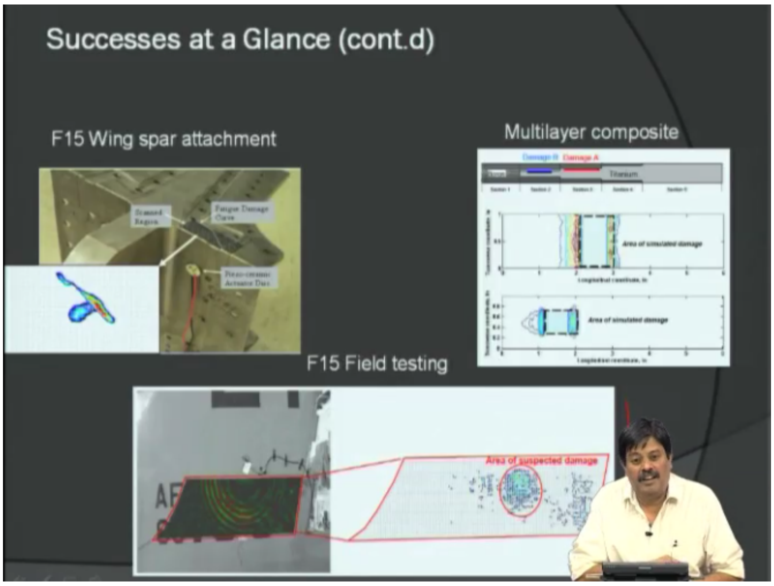

So there are various applications using laser vibrometer that we have done. These are some of the vertical tails that we have done, the plates with multiple delaminations, this is the plate with sheet metal where there is the hairline cracks are there. This is the delaminations in the composites, and here is a case where we have also found out the manufacturing defects in forms of porosity that can be found using this laser vibrometer.

And this is a wing spare attachment which is very complex and the damage is here and by triggering the signal, we could able to do that. And here is a practical case where the section was implemented on a real aircraft and the laser vibrometer we were able to find the place where the damage could have been there.

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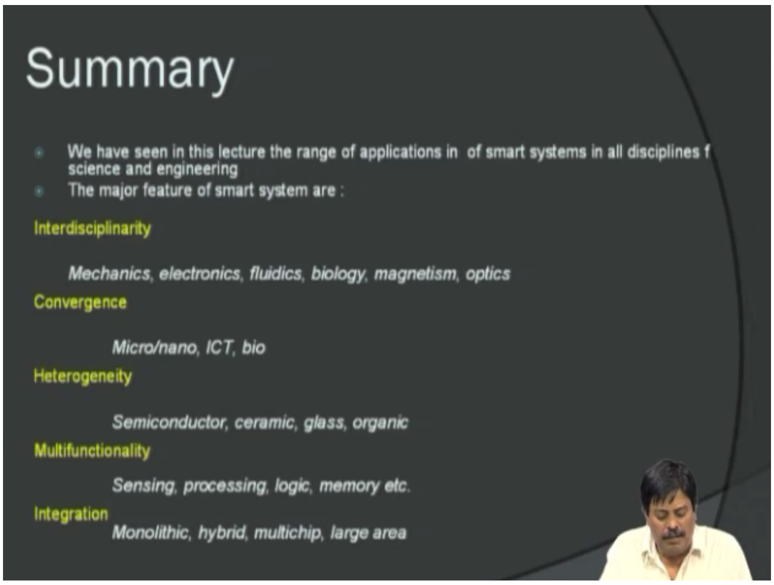

So in summary, what we have seen is the range of applications that the smart systems can have and with the innovations that one can up the applications are endless. So one can have a major, major new systems that one can see coming up in the years to come. The major features of such a smart system is, it is interdisciplinary in area covering mechanics, electronics, fluidics, biology, magnetism, optics.

The convergence of micro, nano and ICT and bio is a place where we can actually build in. The heterogeneity in terms of semi-conductors, ceramic, glass and organic. A multi-functionality, sensing, logic and memory, and finally the integration basically it can be monolithic, hybrid, multichip and large area. So this is going to be endless. so thank you very much, we will end this lecture here.