INDIAN INSTITUTE OF TECHNOLOGY
KHARAGPUR

NPTEL
ONLINE CERTIFICATION COURSE

On Industrial Automation and Control

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Topic Lecture – 05
Measurement System Characteristics

Welcome to lesson number three of the course on industrial automation control so in this course in this lesson we are going to start at level 0 of the automation pyramid and in particular we are going to look at measurement systems or sensors.

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So before we are going to do we are going to look at this measurement system for a few lectures you come so before we do that let us first look at a general measurement systems and try to understand its characteristics so that is precisely what we are going to do today.

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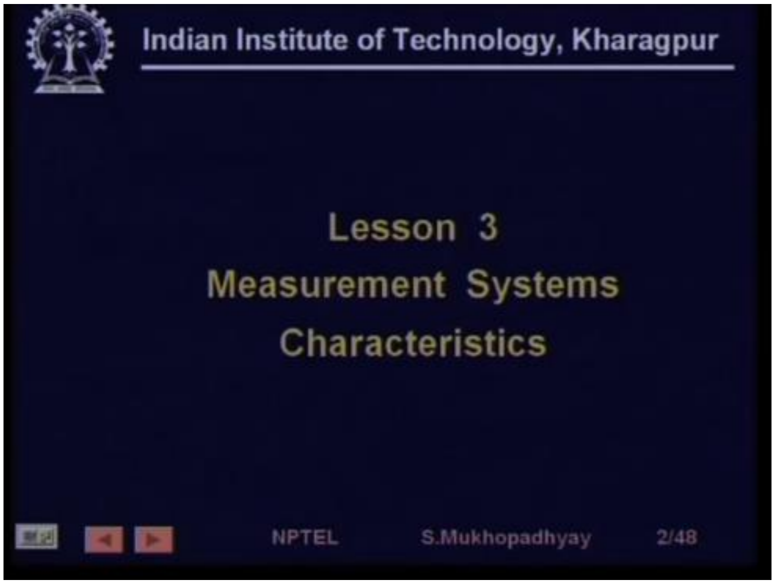

So in this lesson we are going to look at measurement systems characteristics and the and the instructional objectives are the following first of all the most important thing is to learn is the what is known as the static characteristics of sensors and instruments.

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And then the understand what is meant by calibration and what do we how do we characterize errors describe the response of first and second order sensors to dynamic inputs that is most important for control and finally interpret look at some industrial sensor specifications.

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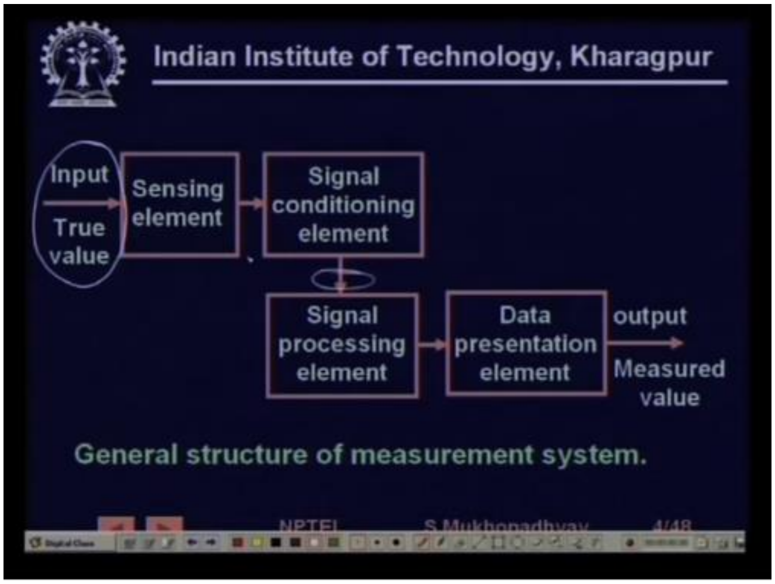

So let us first look at the general structure of a measurement system so all measurement systems can be thought of being made up of you know one or more of these blocks so here is the so here we have the actual measure end whatever signal we are trying to measure pressure temperature that is the signal which is affecting the sensing element so there is a sensing element actually sensing is a is a process of continuous energy conversion from one form from any form depending on what we are trying to measure so from mechanical for more from thermal form or from optical form to finally to an electrical form then the electrical form gets finally transmitted transformed further to you know digital forms etc…

Before their output so through these blocks that conversion takes place so here you have the measure end or the input which is the true value so the real pressure or the real temperature which is the sensing element which exists at the sensing element then the sensing element does the first round of conversion and brings it generally to some sort of an electrical form either in the form of electrical parameters like resistance capacitance changes or in the form of voltages and currents which have to be further manipulated by electrical circuits called signal conditioning elements.

And sometimes you know I mean amplified sometimes the conversion from resistance to voltage so at generally at this level it is in a standard electrical form of voltage but and then some further signal processing goes onto remove noise to make it linear and things like that some of it can be analog some of it can be digital and then finally it goes to the data presentation element or where the data is utilized it can be presentation or application element so it can be a display or it can be a recorder or it can be a controller. So this is the general structure of a measurement system for example if you take an example.

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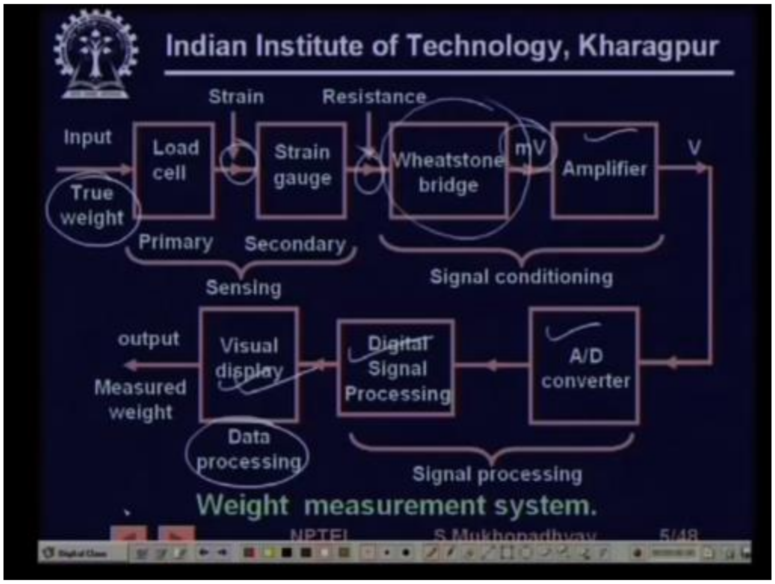

For example here is a weight measurement system so the input is the true weight which is sensed by a mechanical member called the load cell which converts it to strain that is sensed by a by another member called a strain gauge we will we will see all these all these sensors in our future lessons which converts it to a resistance form so you have you see that even there are two sensing elements the first sensing element converts wait to strain the next one converts strain to resistance and then we feed it to an electrical circuit called the Wheat stones bridge which converts this resistance change to a low level voltage mill volts.

So this is the so these are you know signal conditioning elements then it goes to an amplifier which amplifies it to you know standard voltage ranges like 0 to 10 volts then it goes to if we most often it is very convenient to have digital signal processing so we can make it through an A/D converter then input it into maybe some micro computer and do some digital signal processing and then finally send it to a in this case a display so you get a digital display of the reading along with units right.

So that is some more data processing so this is how a real measurement systems looks like so it has it is basically a cascade of several blocks including the sensor the signal conditioner plus some computing elements like the signal processor.

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So sensing is actually extremely important in automation from various points of view firstly in product quality control because the product quality is actually assessed by sensors themselves by some sort of instruments in process control so if you have a rolling mill and if you want to control the role thickness then the your feedback or almost all process control is actually you know a closed loop feedback control about which we are going to learn in the future lessons.

So for that a critical element is the feedback element so the variable which is being controlled it may be thickness it may be temperature whatever has to be continuously feedback using a sensor in the sensor of the control system and the performance of the control system is actually critical to that of this to the sensor so sensing is of primary importance in control then process monitoring and supervision so you know all kinds of you know coordination between machines then fall detection safety measures all this can be done.

Plus providing you know energy efficient optimal set points for doing all this we need sensors and finally we also need sensors for you know manufacturing automation so as we will see when we will even when we will see how the manufacturing automation systems can be put together using let us say programmable logic controllers then you will find that they use various kinds of sensors extensively you know sensors like you know limit switches pressure switches contacts etc… So sensing is extremely important in automation.

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Now so in this lesson we are going to see that if you look at a sensor as an abstract element which gives you which gives you a value which gives you the information about a physical quantity then we need to know how to characterize the behavior of this device called the sensor of the instrument so we need to understand about instrument characteristics and instrument characteristics can be of two types the first is the static characteristics static characteristics implies that of an instrument that concerned only with steady-state readings.

So if you it says that if you apply a 1 volt signal do you get a 2 volt signal, so we are not we are just saying that if we apply let us say we to a to a temperature sensor if we apply 100 degree centigrade what is the output voltage now we are not concerned with the fact when we are discussing static characteristic is that how this how the temperature came from whatever was latest of the room temperature 200 degree centigrade how much time it took what was exactly the way the voltage roles we are not asking about these things we just want to know that if you apply 100 degree centigrade eventually the temperatures settles at what value.

So you know that would be a static characteristics now static characteristics are important for indicating instruments whether indicating instruments are generally concerned with steady state values or for worry or for instruments where the dynamics is actually very fast that is this settling from whatever was the temperature to the hundred degree centigrade temperature is so fast that are that for all practical purposes we can neglect the way the temperature roles that is does not concern us.

In such cases these static characteristics is of importance while there are cases where dynamic characteristics is also important especially in control because as we shall see later that the performances of control loops for example when you are trying to control essence of feedback control is that suppose you're saying that this temperature should be maintained at 100 degree centigrade.

Now if the temperature sensor has a 2 degree centigrade error by which I mean that suppose when the temperature is 90 degree 98 degree centigrade the sensor is telling you that it is hundred degree centigrade it is giving you a wrong information by which is wrong by 2 degrees then the controller has no way of knowing the actual temperature 98 it actually thinks that it is hundred degree centigrade and it tries to maintain it at that that temperature while the actual temperature stays at 98 degree centigrade.

So you have a steady state error right, so you have a real error that is that physical real temperature will be 98 while the controller will think that is 100 so such errors occur due to do controllers and due to errors in sensors number one and number two is that now this errors can sometimes we be reduced by you know designing the gains so it sometimes happens that we need to not only maintain fixed temperature sometimes we need to track temperatures so in such a case if you do not get the readings as they are existing then what happens is that the temperature develops what is called a phase lag that is the controller develops of phase lag.

And it will not be possible to exactly track you know moving commands so in such cases dynamics of these sensors are actually important.

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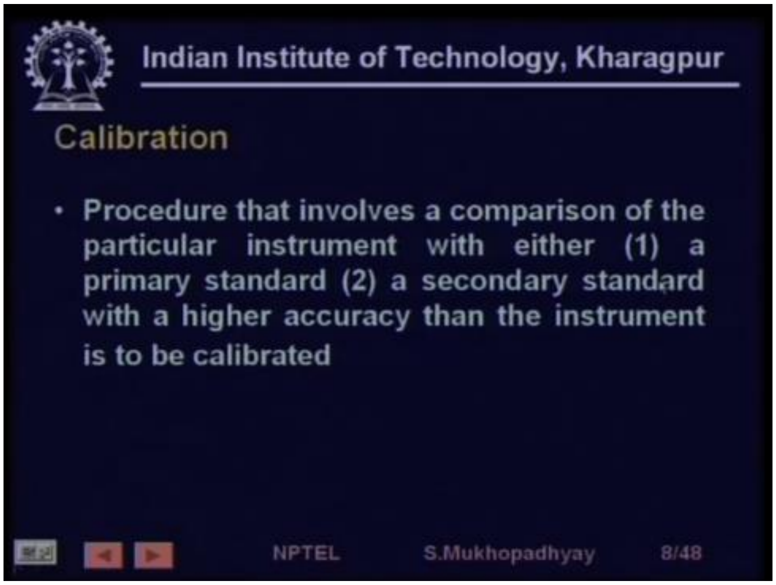

So we will look at both sensor and both static and dynamic characteristics and before we look at this characteristic we need to understand how they are obtained so they are actually obtained by a process called calibration, so basically a calibration is you know we are saying that if the true value is so and so what is the, so calibration is basically when you say static when you say characteristics of an instrument what you mean is what is the input output characteristics so if the true value is so and so what is the output that is what that is what is it essentially to be determined.

Now the point is that the true value can never be known so therefore how do you assess the true how do you get the true value so essentially what we have to do is that we have to measure the true value again using some other instrument which for scientific and technical reasons we actually believed to be much more accurate so it is always calibration is essentially a comparison between the instrument that is being calibrated and another instrument which is assumed to be the true value.

So such instruments depending on the calibration situation for example if you are calibrating if you are calibrating there is a there is actually a calibration change in the sense that when you are calibrating some instrument in the factory it is not possible for all variables there are some very, very accurate instruments which are maintained in under special conditions in you know you know national standards laboratories but when somebody is calibrating let us say in a short floor it is not possible to possible that that every instrument will be calibrating international standard.

So therefore there are secondary and tertiary standard equipment so anything we will have to be calibrated against such an instrument. So that is what it says that with either a primary standard or a secondary standard with a higher accuracy then the instrument is to be calibrated.

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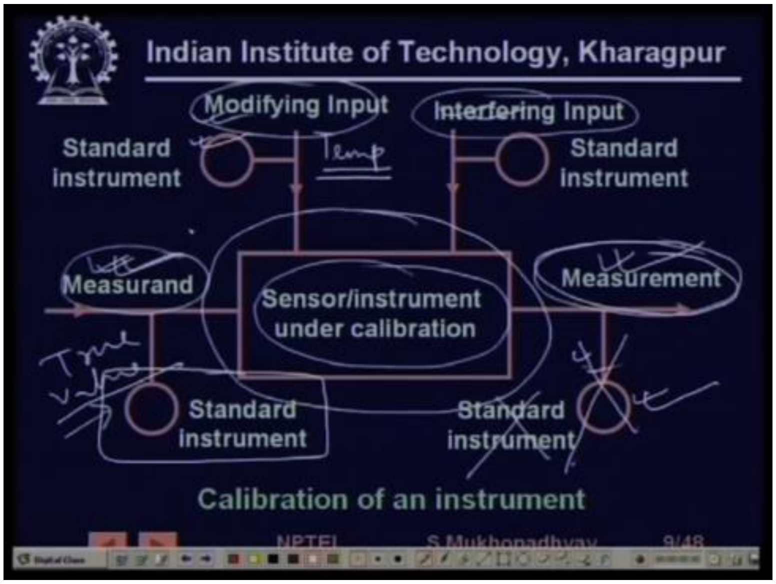

So this is this is the essential scenario that you have a stack this is the sensor instrument which is to being calibrated now the reading the you are first of all you are look at the fact that this is the measure and whose which you are measuring using some standard instrument and you are thinking that this is the true value this is an assumption you are also measuring nowhere this is not required I do not know why this is this is connected this diagram is drawn wrongly so the sensor instrument of the calibration is giving a measurement.

Now this measurement again for example suppose it is a voltage then how many volts it is that again will have to be measured by some instrument so that maybe this instrument right so in that sense this is required so you have to you have to measure the measurement if the measurement is for example given in a digital form then you do not need to measure it then you can so this may be there or not there on the other hand there are you know this sensor this instrument reading or the measurement is actually a result of not only the measurement.

It is a result of many other factors for example it may be a result of temperature for example if you take that if you take the weighing weight measurement case then the then the strain gauge resistance change is not only a function of the weight you put it is also a function of the temperature because every resistance has some temperature coefficient.

So if the temperature varies then the resistance is going to change similarly there are various kinds of interfering inputs like for example there may be some noise there is some noise induced from a power supply or from some power line or especially in the in the industrial environment there are plenty of noise sources and these sources these signals can also affect the sensor measurements so generally when you to the extent possible when you are trying to calibrate an instrument you will have to also note what are the model for example what is the temperature.

So if you so that you can actually apply the corresponding Corrections and you can characterize when you are trying to characterize the instrument you will also have to characterize it is response with respect to these kind of inputs I mean in some cases it may not be possible to measure this kind of interfering inputs in such cases we try to ensure that these interfering inputs are not present.

So we do shielding we actually do take it to a different setting and actually try to see what the sensor is doing so essentially we try to measure the measurement we try to sense we try to also measure the output of the instrument and we try to measure modifying inputs like temperature and then we establish the characteristics of the instrument, so since the instrument must have been constructed to be you know relatively unaffected by modifying input so I mean generally what is of much more importance of primary importance is to see how the instrument characteristics are dependent on the measurement right .So that is what we are going to look at mainly now.

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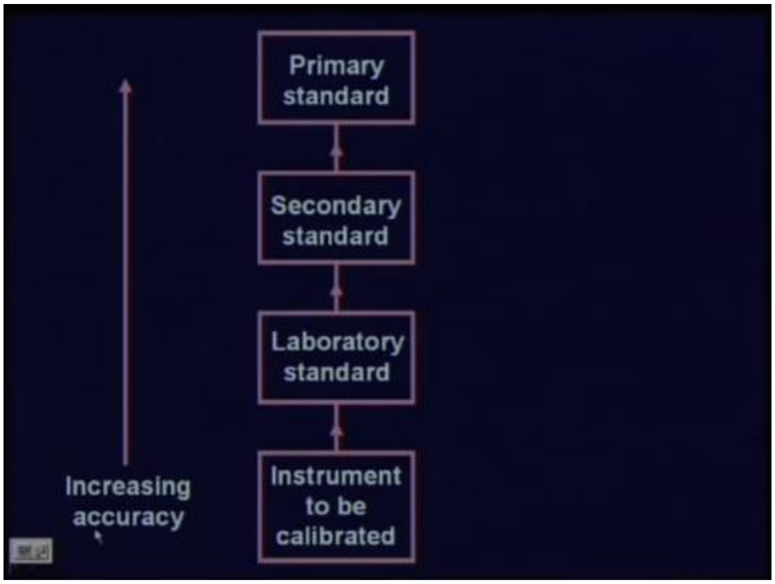

So this is what it says that this is what I was talking about that there are different standards of instruments so the instrument we calibrated can be calibrated against the laboratory standard now the laboratory standard instrument also has to be from time to time calibrated against you know other standards like you know secondary standards which are straight which has special instruments which can be you know existing in some test houses and then.

So you from time to time you have to send these instruments to the test houses and get them calibrated on the other hand these tests house instruments again have to be calibrated against in some very accurate national standards, so in this way you have you know what is the called a chain of standards of increasing accuracy and at different levels you always calibrate according to a with respect to an instrument which is at the at the next level according to the chain.

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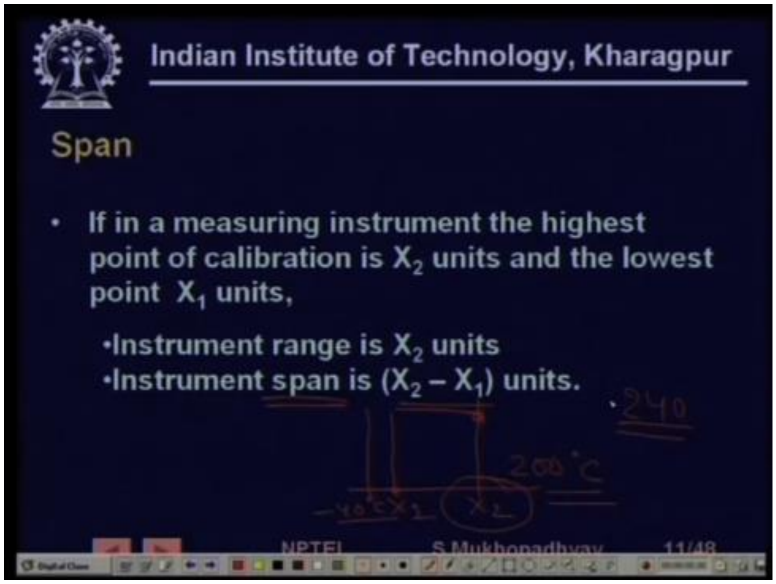

So let us look at these static characteristics so we begin with span so it says that if in a measuring instrument the highest point of calibration is X_2 units and the lowest point is X_1 units so what we are trying to say is that the instrument is has been used between two points so the instrument has been calibrated to work between two points right and this is so this is X_2 and this is X_1 then the instrument range is X_2 it is the highest so it can work up to that value and the and the span is $X_2 - X_1$.

So if this is 200 degree centigrade and if this is -40 degree centigrade then the range is 200 and the span is 240 right so that is pretty obvious so we have to remember these two details.

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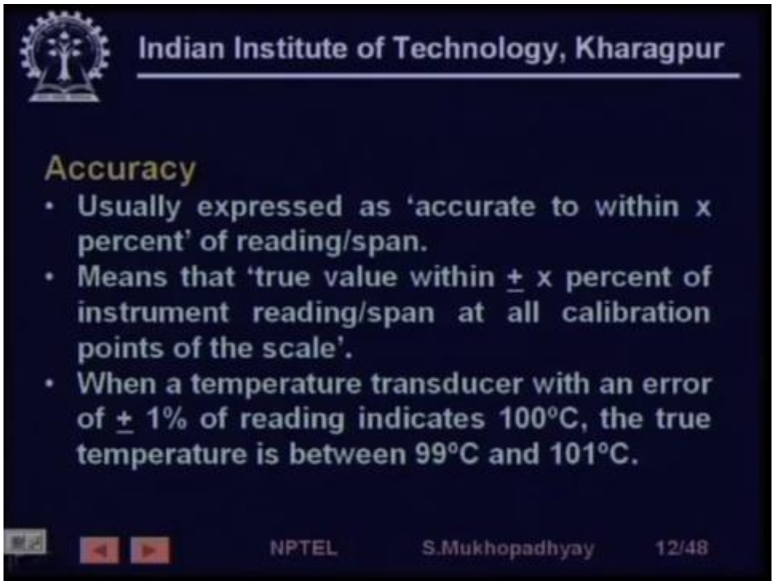

Next let us talk about one of the most important parameter called accuracy so accuracy if you see instrument specification there will be there will be generally written as accurate to within X percent of either reading or span sometimes they say reading sometimes they say spam in fact sometimes they also mentioned constant values that is accurate within plus minus 1 degree centigrade so if when this constant value then since the span is a constant quantity so you can always express it as a percentage of span also right.

So the span is 100 degree centigrade then a an error is of plus minus 1 degree centigrade can be expressed as 1% of the span so it is either a constant value it may be expressed with the percent of span or it is a percent of the reading okay so what it means that is there if a reading is 100 and if it has plus minus 1 percent of let us say span accuracy then the reading is somewhere within let us say 99 and then the true temperature will be between 99 and 101 degree centigrade and this so at all points so whatever reading you get you can always basically these are needed because the because the user of the instrument needs to know that in within what values.

So it gets the reading but within what is the guarantee that the true value will be staying within certain limits so that limit is stated by accuracy but then again the true value is unknowable and it is actually what you stated is that with respect to the calibration so then the next point is linearity.

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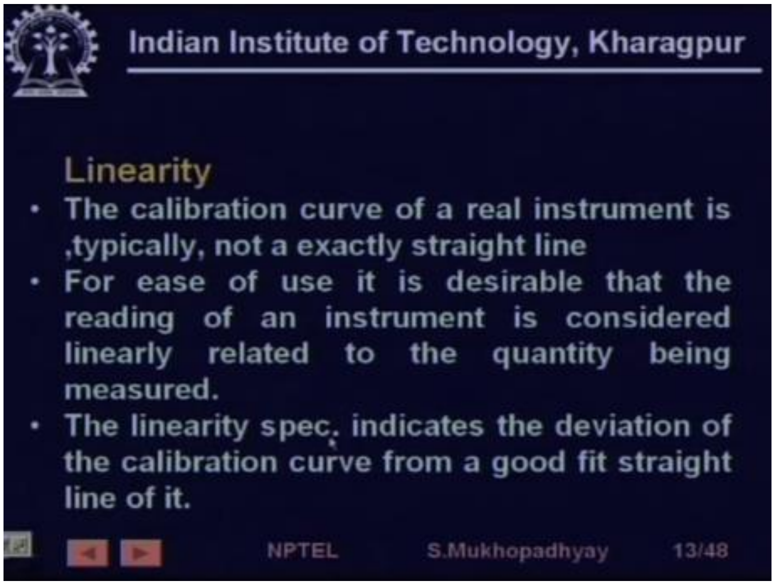

You know we generally want although instrument calibrations will not strictly follow a linear curve but still it is very useful to imagine the system as a linear one so you know if you have a so that you can very easily interpret the true value so if you have an instrument sensitivity of let us say 10 mill volts per degree centigrade then if it gives a 25 mill volts signal then you know that it is that the temperature is 2.5 degree centigrade.

So you can get just by dividing by a number or sometimes adding another number to it so it is from that point of view from the point of view usability it is very attractive to express at the characteristic of the linear one but then it is not linear so therefore while you mention a line which can be which can be used for deducing the true value from a reading you also have to give some bounds within which the true value will remain because it is not exactly going to because the instrument does not actually follow that line characteristics the line is only an approximation.

So when you when you are telling the user to use the approximate model of the line for simplicity you also have to tell him what is the kind of error that he or she can expect if she uses that uses the linear model of the instrument so that is given by the measure of linearity so the linearity specification indicates the deviation of the calibration curve from a good feed straight line so now how do we how do you obtain this straight line we can obtain the straight line in various ways.

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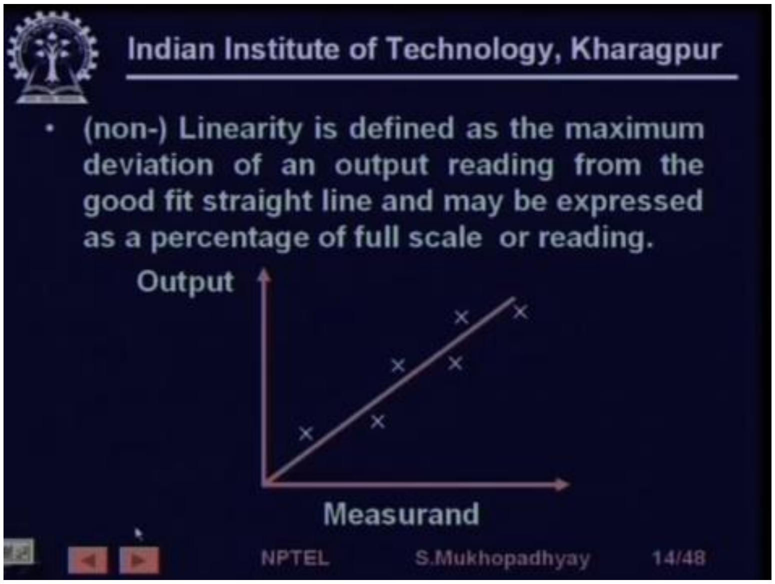

So one way would be this that we actually perform some calibration experiments so you got these data points so you got this data point these are experimentally obtained so for all you know the true characteristic of the instrument let me use a white color that will be good so for all you know the true characteristic of the instrument may be like this and you are approximating it by this straight line, so you have to also say that if you use the straight line characteristics then the true value is going to be within which limit.

So that is why when you say linearity actually the linearity specification is actually a nonlinearity specification in the sense that it indicates deviation from linearity so it is defined as a maximum deviation of our output reading from a good fit straight line so obviously you want that so obviously you want that the straight line that linearity specification is small, so that you are telling that if you use that straight line characteristic you are not going to have much error that is what you are telling to the user.

So that it is the smallest possible you have to actually take all the data and make up a best fixed straight line such that the sum of square of errors is the least or something like that, so that is that is linearity but it is the deviation of the calibration data from some good straight line which you have obtained either by data fitting or in some cases it may be obtained also in a different way.

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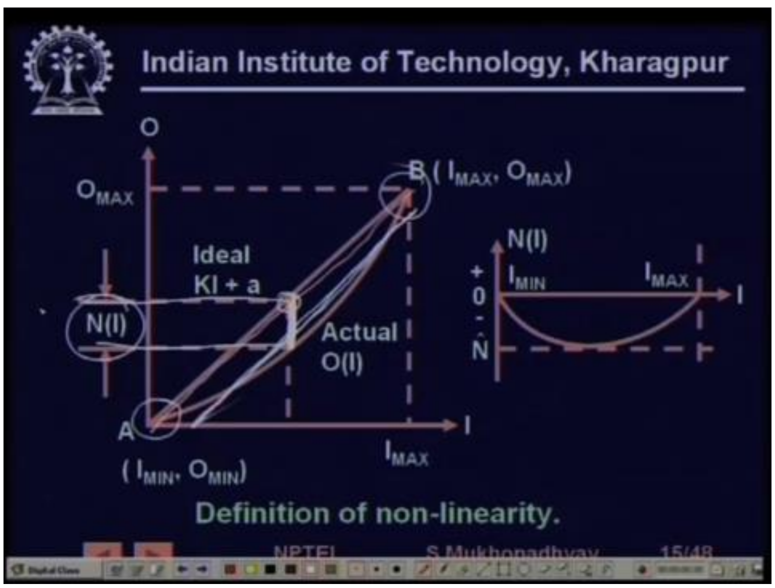

So for example in this case you can also obtain it that is a simpler way by taking the reading at the least value and the maximum value and then simply assuming that the characteristic is going to be like this now this is not the best fit line probably for this curve the best fit line would have been like this however in some in some cases you can perhaps use this line that is actually a simple thing if it does not matter so basically non-linearity whatever is the line once you have fixed the line the non-linearity is actually this deviation.

So here it has the maximum deviation, so the non-linearity pack or which is we actually refer to as a linearity pack is actually deviation from that line right.

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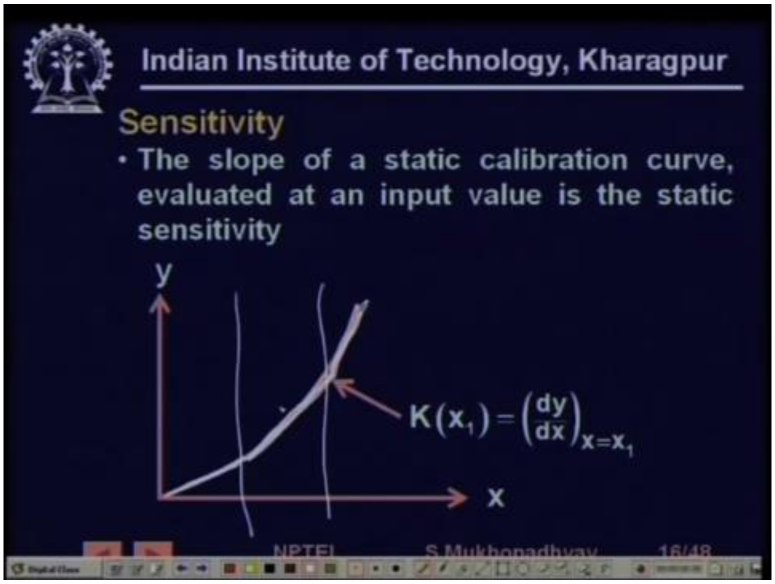

So next we are interested in sensitivity so sensitivity is actually the slope of the line so if you have a calibration curve and then so that that will be the sensitivity and if you have a calibration curve and then get a straight line in case you have a linear characteristic it will have one single sensitivity if it is very nonlinear then sometimes you may also express it as so you can take do actually do various things you can express say let us say three sensitivity figures.

So one sensitivity figure will apply this range the other sensitivity figure which is a average slope of the line in this range and then another sensitivity figure which will apply in this range or you can so basically sensitivity is the slope of the characteristics so depending on the non-linearity you have you can use multiple slopes on multiple ranges sometimes instruments do that.

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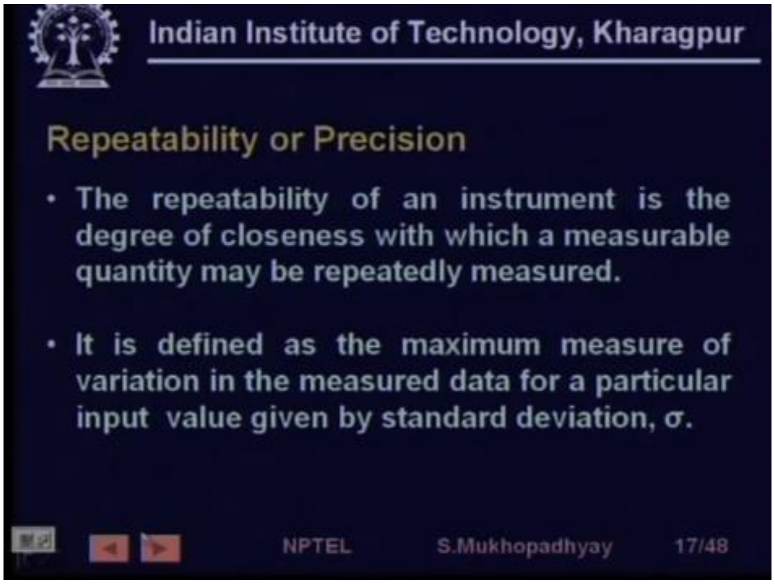

Similarly we are also interested in what is called repeatability or you know precision in the sense that we want we do not want that today we make a measurement of the temperature of boiling water so it is giving me some reading tomorrow if I take that reading should be should be nearly same it may not be exactly same but if but it should nearly say so when it is very close when you if you take multiple readings if they are very close then the then the instrument is said to be repeatable or precise right.

So repeatability of an instrument is the degree of closeness with which a measurable quantity may be repeatedly measured right, so we go to the next one.

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Which is resolution this is also where it says that how much of change in input will actually cause a detectable change in the output so what is the smallest change in the input so if so can we detect a change of point one degree centigrade or can be detect a change in point zero one degree centigrade for example if you have a clinical thermometer then you cannot possibly detect a change of .01 degree centigrade or .01 one degree Fahrenheit generally they are calibrated in terms of Fahrenheit.

So that is the resolution if a temperature transducer is resolution is 0.2 degree centigrade then is the smallest temperature change that can be observed.

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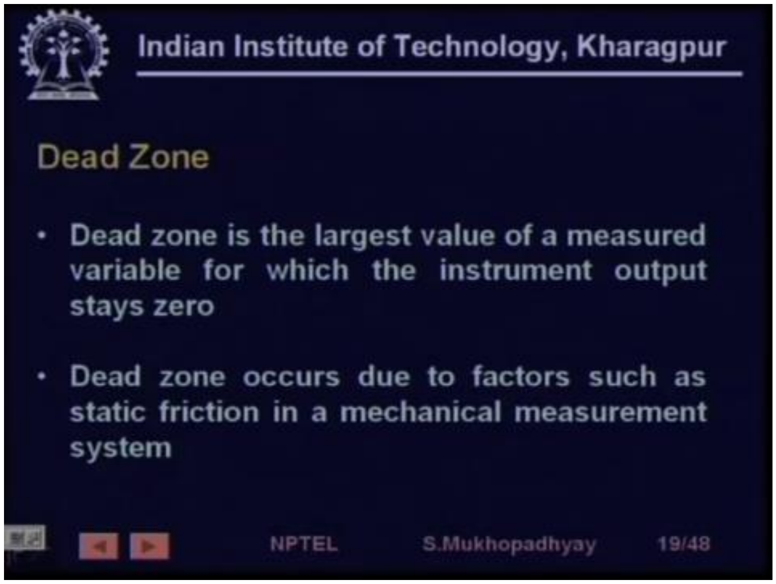

Okay similarly we have similar to the concept of dead zone sometimes you know sensors systems will have dead zones for example we often find that you know this electrical meter sometimes they will stick you know any mechanical arrangement tends to develop something like a static friction which also developed depends on many things like temperature time humidity and other things.

So what happens is that till say if you have ammeter then till you send a certain amount of current the torque is not enough to overcome static friction so the so the needle does not move so it is a so dead zone is a largest value of the measured variable for which the instrument output stays 0 so from 0 to that value there is going to be no deflection no reading nothing so that is called a dead zone.

So what is the difference between the dead zone and the resolution dead zone is the is actually the resolution from 0 while resolution is resolution can be resolution from 24. 24 to 24.1, 24.1 to 24.2 while generally dead zone is refer to from zero so it occurs due to factors such a static friction.

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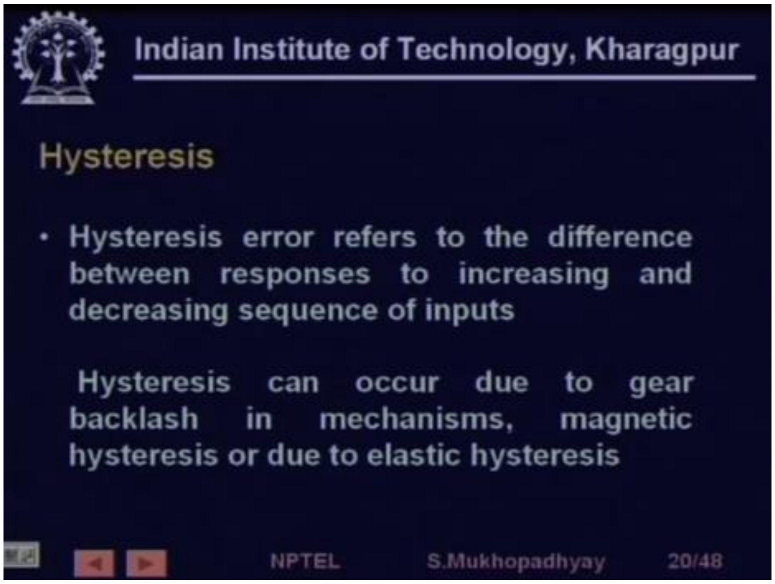

Similarly sometimes we have we have hysteresis in instruments so that if you have an increasing sequence of input values if you are increasing the input from let us say zero 10 degree centigrade 20 degree centigrade, 30degree centigrade, they are increasing sequence of values then we get one set of readings while if you have a decreasing set of values then we get another set of readings and these readings are distinctly different right so in that case we say that the instrument has an has a hysteresis it can occur due to various factors like you know gears backlash or it can occur due to you know magnetic components or sometimes by due to you know hysteresis which occurs due to elasticity. So do such things the hysteresis can be there so what is.

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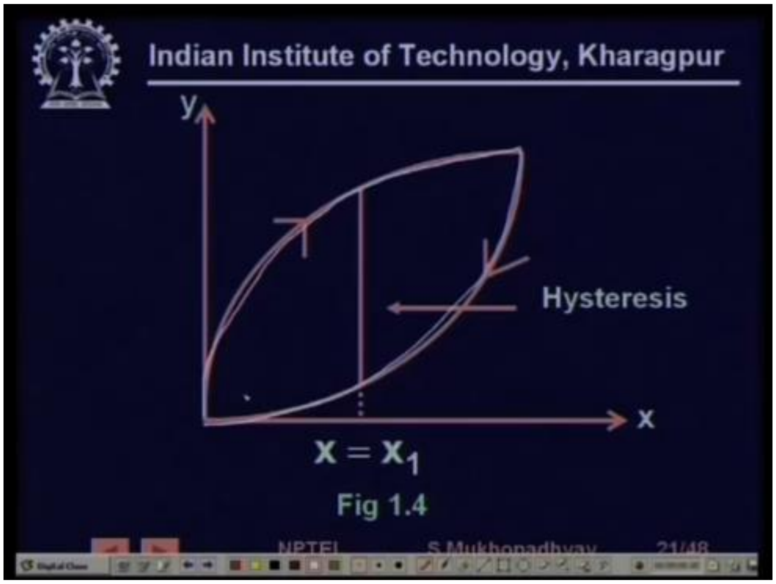

So this is the figure that we are saying that the if X is increasing then the then the readings that we obtain follow this curve while if X is decreasing we actually forward distinctly different curve so if such behavior is demonstrated by an instrument it is called it is said to have hysteresis.

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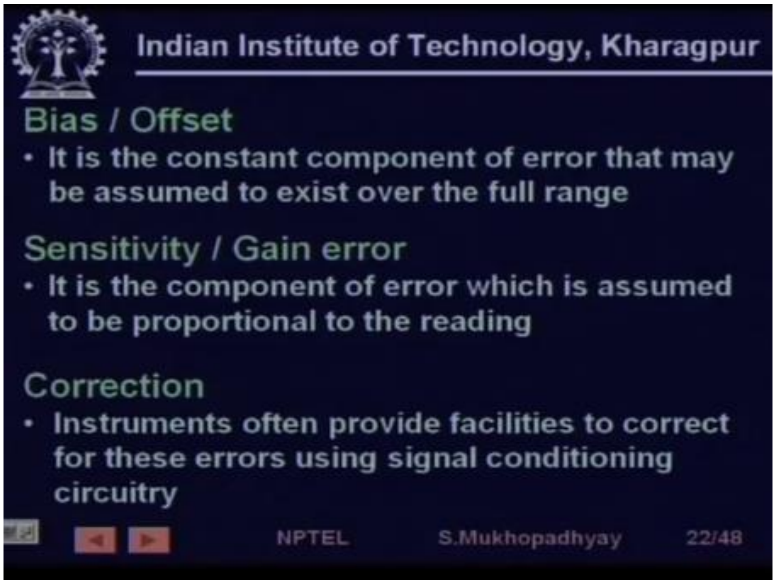

So next so now the errors that we have you know that so we have actually typically an instrument is supposed to have a supposed to have a calibration curve but the reading that it has may not exactly match with the calibration curve it is if you read outer diameter then it has some scale fixed but if you send exactly one ampere current then the then the needle may not stand that one ampere.

So this is the error now the error is typically you know characterized as in into two different kinds so since the instrument is actually assumed to be a linear instrument so it is assumed that the error can be of two types the first type is called bias or offset which is a constant error which is which is going to stay throughout the range so maybe at half at when you have a reading of when you have an actual current of 2 amperes you are reading shows 2.5 when you have 3 ampere is showed 3.5 when you have 10 amperes shows 10.5.

So you have a point 5 ampere of biases right if you see ammeters normal ammeters you will find that such biases can be corrected by you know screwdrivers that there are they are also sometimes called zero adjusts similarly there can be see there can be a gain error so you have a sensitivity while we have a nominal sensitivity which is indicated by the scale and your actual instrument sensitivity may actually deviate from that and then you have a sensitivity or gain error and the error in reading due to this gain error is going to be proportional to the reedy.

So if you have if you are measuring 10 degree centigrade then the error due to gain error is going to be half off if what you measure due to 20 when you measure 20 degree centigrade so we assume that the errors are of two kinds and these typically in typical sensors and instruments very often they can be corrected by electronic signal conditioning means.

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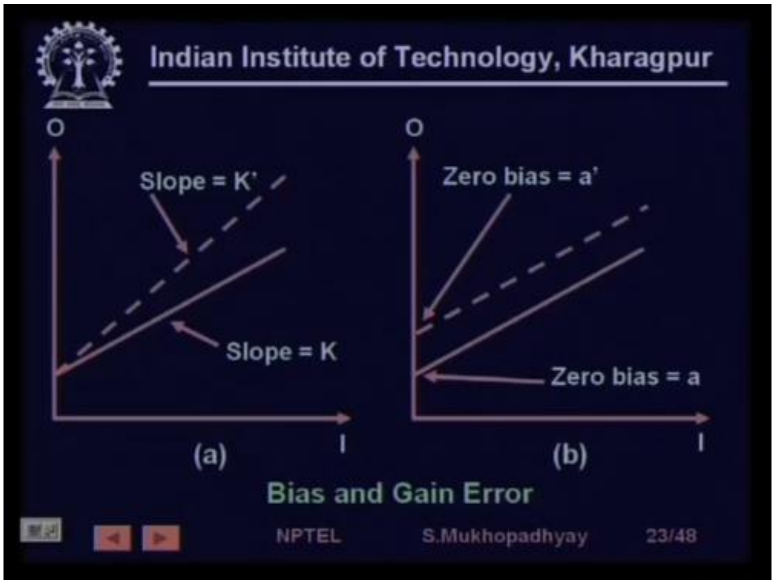

So that is what is depicted that if you have a zero error so that is a bias and if you have a slope error that that is a gain error.

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Next is drift so sometimes what happens is that even if you correct even if you correct at any at some point of time during calibration even if you correct for the bias on the gain error you have drifts in the bias on the gain so gain such bias and generals can develop due to you know variations in temperature variations in time or some other conditions so the rate at which it these will develop our are characterized by a performance characteristic or drift.