Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
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Week – 02
Lecture - 06
**Overview of Measurements in Fluid Mechanics – 2**

An example, for example, is this strain gauge sample that is being shown over here, once again, from the book. So this is, for example, what you are sensing. This is a strain gauge. That is put on a cylinder, for example, and the cylinder is undergoing some kind of tensile loading in this case. So, this is a strain gauge. Same examples happen everywhere.

It is now connected to a bridge. So this is your conversion part. Then it goes to an amplifier filter. Filter, we already know what it is.

This is the conditioning to remove extraneous signals and things like that, and also to amplify the signal. And then, subsequently, this data is passed on to a DAQ or a DAC. So this is conditioning and storage. This is storage. So this part is basically transmission.

A strain gauge is a sensor whose electrical resistance is sensitive. So here, the resistance actually changes when you stretch it. Therefore, as you elongate, it gets stretched. As a result, you can sense it. This is wired now to a Wheatstone bridge, which we call a bridge over here, which converts the change in resistance into an electronic voltage.

Further use of an electric amplifier and a low-pass filter, which conditions this voltage to a measurable low-noise electric signal, is subsequently transmitted to a DAC or can even be displayed on a computer. Whatever it is that you want to do, it can also be used. For further analysis. So this is how this actually happens. So you can see all the parts of how this is done.
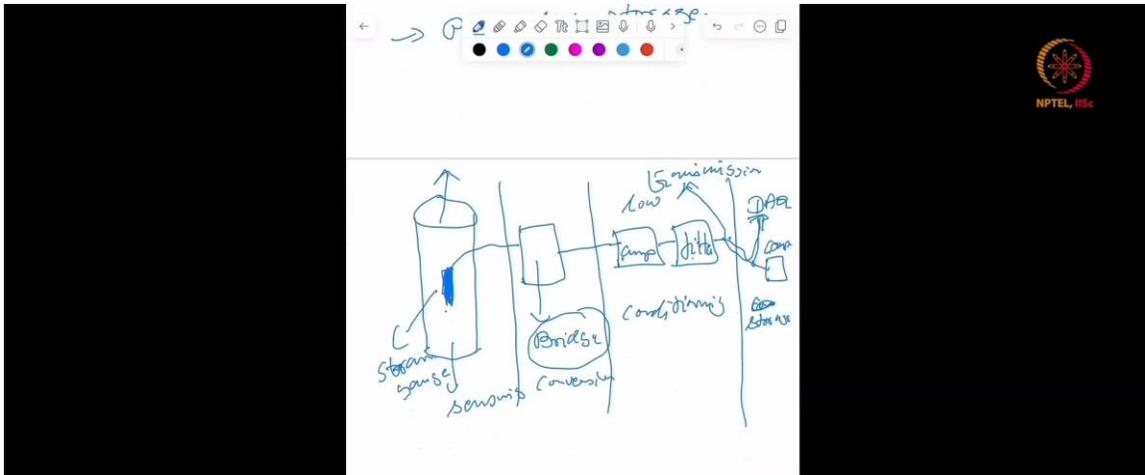
So what is transmitted is basically a low-noise signal. So this is where it is converted into voltage. Right? So, as you can see, this is a very nice operation. So similarly, you can have static response and static calibration. So static response and static calibration.

Okay. The operation of a measurement system is called static when all its inputs and outputs are either constant or varying very slowly with time; okay, so you have a measurement system where all its inputs are not a function of time, so inputs are not functions of time. Whatever output you are producing is also not a function of time. Even if it is a function of time, it's a very slow function of time. So, what happens is that as the input changes, the output changes, but they are not time dependent. So this is what is called a static response.

The relationship that provides a value of the input as a function of the system output during static operation is called the static response of the system. So, static response, okay? Response during static operation of a system. All right. The static calibration is preferably performed separately for each desired input. OK, so that means you provide all the inputs and then you know what the static values are.

OK, so that the values of this input are measured independently. by some other instrument

whose   response   is   known.
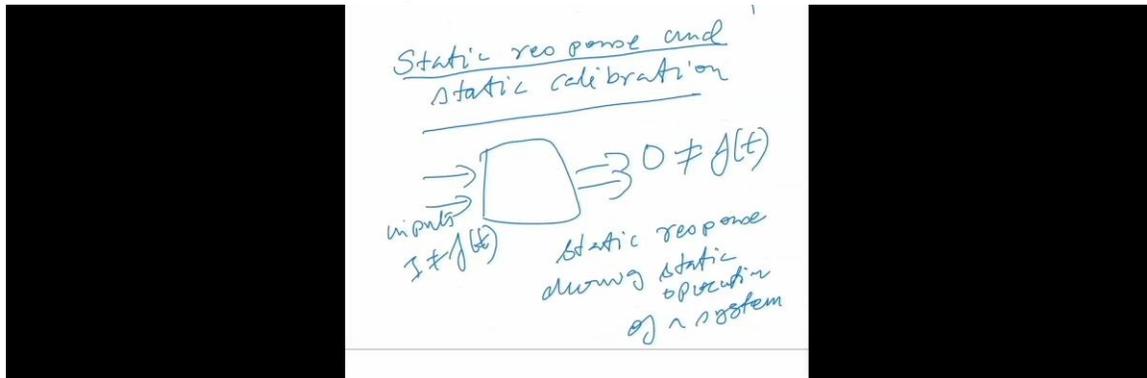
So we are trying to see what the one-to-one mapping is between the input and the output in this particular case. The values of the input are measured independently by another instrument whose response is known and that serves as a standard. Sometimes it is impossible or difficult to maintain all but one input constant because changes in the desired input may trigger changes in other inputs as well.

So that there is some sort of coupling that goes on between the input. In such cases, all changing inputs must be measured during calibration, and different effects must be identified and separated. All possible interfering and modifying inputs during calibration should be maintained at the same level. The undesirable inputs may distort the static responses. So if you have an undesirable input, what it will do is distort the static response.

Static response by introducing what we call drift, zero drift, namely a parallel shift in the calibration curve, or a sensitivity drift, which means the change in the slope of the calibration curve. So if this is your calibration curve, a drift could be like this. So this is zero drift. Or it could also change this, which is basically a sensitivity drift. All these undesirable inputs can actually do that.

This is input; output, or rather, this is input. This is output. This is input. Out calibrate. So, for example, there are two types of static response.

Consider the measurement of a pressure difference between a gas using a liquid manometer and a variable reluctance pressure transducer, which you know is not effective. In the first case, the input is related to the difference in height determined by hydrostatic law. In the second case, the same input is correlated with the electric voltage by certain approximations.
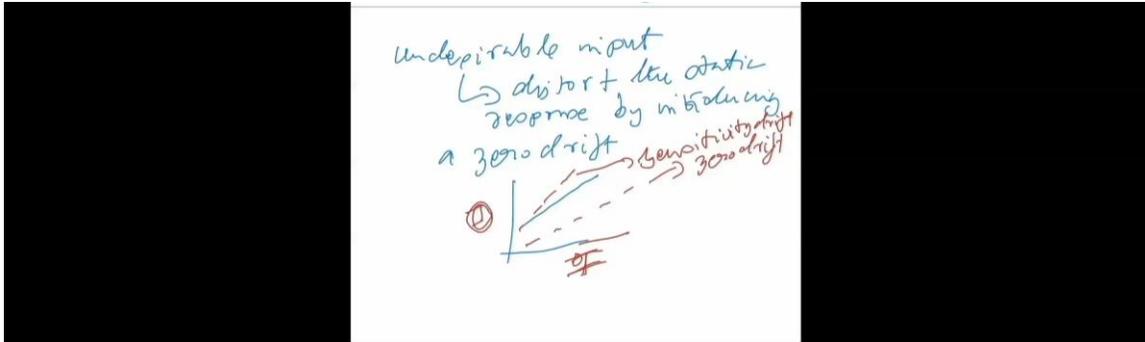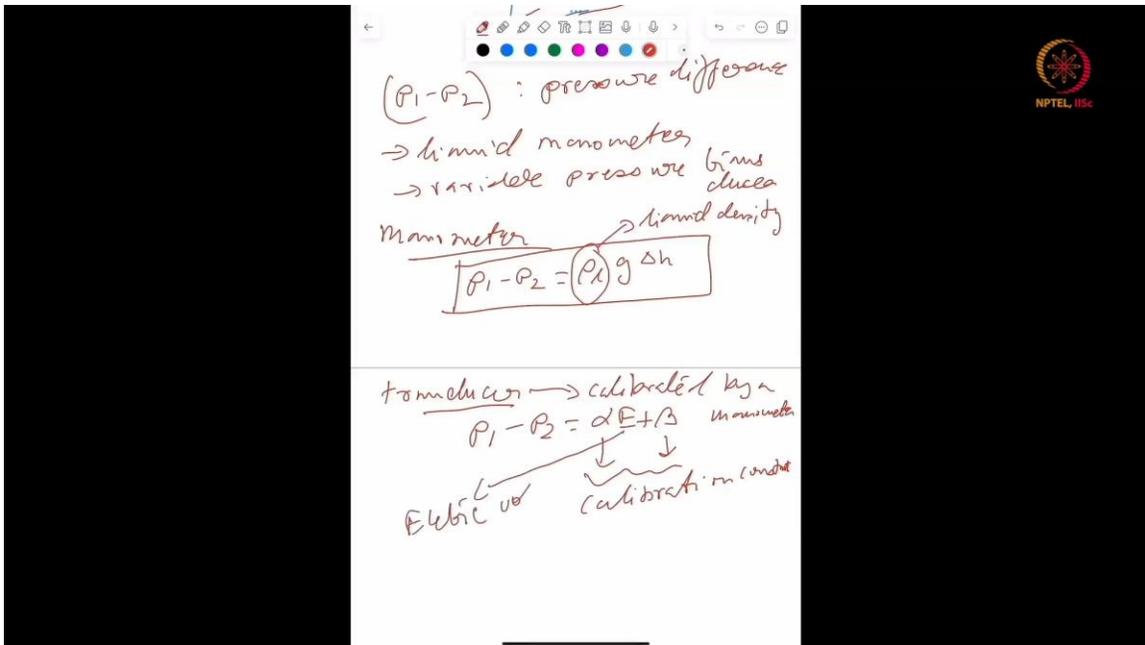
So, for example, you want to measure the pressure difference. The $P_1 - P_2$ is the pressure difference.

Pressure difference is what you want to measure. Now, this pressure difference, which you want to measure, can be measured by using a liquid manometer, okay? Or a liquid manometer or a variable pressure transducer. This is the premise, right? So how does a manometer work? A manometer is pretty simple; it is $P_1 - P_2 = \rho_l g \Delta h$. This is what the manometer will be. Okay, so rho l is the liquid density.

In the second case, this is what the pressure transducer, or the transducer, is going to do. It is going to measure the same thing, but by electrical means. It is $\alpha E + \beta$, where these are the calibration constants. which is measured through calibration. But this is done by calibrating the transducer using a manometer.

So the transducer is calibrated with a manometer. Because what it measures is basically the electric voltage. So this is the electric voltage. So this is also measured by a strain gauge. There's a strain gauge in between that gets deflected, which leads to that, okay? So, the static sensitivity is the slope of the input-output relationship.

$$(P_1 - P_2) : \text{pressure difference}$$

→ liquid manometer
→ variable pressure transducer

Manometer → liquid density

$$P_1 - P_2 = (\rho) \, g \, \Delta h$$

transducer → calibrated by a manometer

$$P_1 - P_2 = \alpha E + \beta$$

Electric volt   Calibration constant

 If you put it like this, static sensitivity is basically the slope. So, if you have an input-output, this is the slope, okay? of the, so this will be the slope. So these curves can be anything. It can also be like this. So the slope may also be a variable slope.

 So, if it is a linear slope for a linear system, the slope is constant. Whereas nonlinear systems will have a local sensitivity that varies with the input range. So this might have different slopes. So, a static sensitivity is good. Then let me quickly say that there is something called scale readability, which refers to analog instruments.

 It's the minimum change in output that can be recognized by an observer. This is, of course, also subjective. Then the span of the full scale is a range of input that the measurements are designed to measure. And then there is full-scale output, which is the algebraic difference between the output values and the maximum and minimum input values. And the dynamic range, I think this one; I'll write it down.

 The dynamic range is basically the ratio of the largest to the smallest value of the input. The largest value of the input divided by the smallest value of the input. This is what the system can measure. The linearity is the maximum deviation from this linear scale. So, linearity is a measure of actual non-linearity.

 So any deviation, the manufacturer specifies linearity as a percentage of the instrument's reading. The threshold is the smallest input level that will produce a detectable output. The threshold is the smallest detectable input level. That is detectable.

→ Static sensitivity → slope is constant.
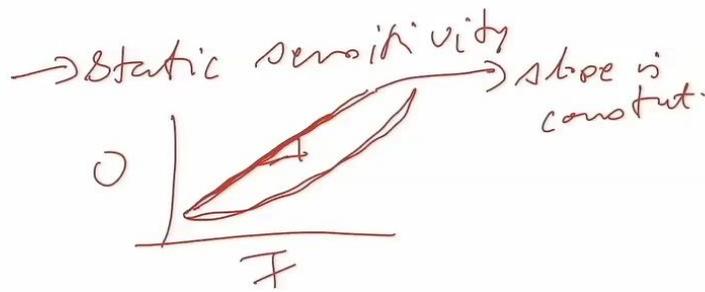
→ Dynamic range
Largest value of input / smallest value of input

→ Threshold: smallest input level that is delectable.

Similarly, the resolution will be something that is the smallest input change that will produce   detectable   results.

There can also be features like hysteresis. The hysteresis is the difference between the output value corresponding to an input value and the difference between the output and the input. So output the value that was reached while you were going up versus going down from   below   and   from   reaching   from   above.

So if you go from 0.1 to 0.2, and then come back like that, it is something like hysteresis, either up or down. Okay. And then, of course, you have other things like normality tests, removal of outliers, and stuff like that. There will be some value. By repeating the measurements,   you   want   to   check   whether   all   these   values   are   consistent.

Not so, there are normality tests; beyond that, we are not going to go into the details. You can also identify trends by looking at the process under statistical control, so you can do all this, then sub-fitting linearization of the data. There are lots of things that one can do.

→ resolution: smallest input change that will produce a detectable output change

→ The hysteresis
$\Delta = (\text{output} - \text{input}) \updownarrow$

Okay, and all these things you can check, so let us just quickly look at the dynamic response of measuring systems because this is not a full-fledged measurement course of that kind. You can read up on all these things from the book.

Okay, so the operation of a measuring system is called dynamic if at least one of its inputs is time-dependent. It can have multiple inputs, but at least one has to be time-dependent. Unlike static response, which is usually prescribed by an algebraic relationship, dynamic response is generally specified by a differential equation. It is specified by a differential equation. The dynamic response of systems is usually modeled by mathematical equations describing the physical principles, such as circuit laws, momentum balance, or energy balance.

Dynamic response of measuring system

→ Dynamic response is specified by a differential equation
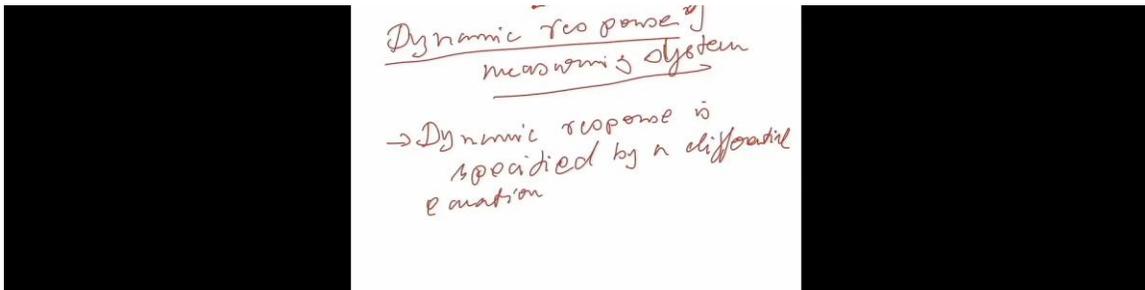
And the output depends on several inputs. The full mathematical model would likely be a set of nonlinear coupled partials. So, stuff like that. So let us look at a few of them, such as a zero-order system. A zero-order system is characterized by a single parameter. Say, for example, $y = kx$, where the static sensitivity is k.

Has the same dimensions, the ratio of y over x; the dynamic response of a zeroth-order system is independent of time. The dynamic response, you should say, the response of a zeroth-order system, is dependent on time. The output remains proportional to the input at all times. So output and input remain proportional to each other. Examples of these zeroth order systems are electric resistors.plastic spring. So, these are examples of zero-eight order systems.

Zero order

$y = kx$

static sensitivity

Dynamic response of a
zeroth order system is
independent of time.

→ electric resistor
→ elastic spring

Then you go to the first order systems. This is first order. So, what first-order systems are is $\tau \frac{dy}{dt} + y = kx$, characterized by two parameters: one is the static sensitivity, and the other is basically the time constant. So, you know, examples of such systems will be the resistor-capacitor systems, for example.

First order system

$\tau \frac{dy}{dt} + y = kx$

↙ time constant.   static sensitivity

→ resistor – capacitor

Then there will be second-order systems; see here the time constant comes that the second-order system is characterized by three parameters: the $\frac{d^2y}{dt^2} + 2\zeta\omega_n \frac{dy}{dt} + \omega_n^2 y = k\omega_n^2 x$, where y equals, so one is basically, once again, this is the static sensitivity. And then there is an undamped natural frequency. This is undamped natural frequency.

Okay. And the last one is basically the damping ratio. Okay. So this second order system is called undamped. So this system is called undamped, undamped in equal to zero, and it is called underdamped, underdamped, okay? When this is zero, it is less than one. And then the last one is critically damped.

There is an overdamped also. Critically damped when this is equal to one and overdamped when it is greater than one. So these examples of this that can be represented are a liquid manometer. So one type of system is a liquid manometer.

Second order system

$$\frac{d^2 y}{dt^2} + 2\zeta\omega_n \frac{dy}{dt} + \omega_n^2 y = K\omega_n^2 x$$

damping ratio — undamped natural frequency — static

→ undamped when $\zeta = 0$
→ under damped when $0 < \zeta < 1$
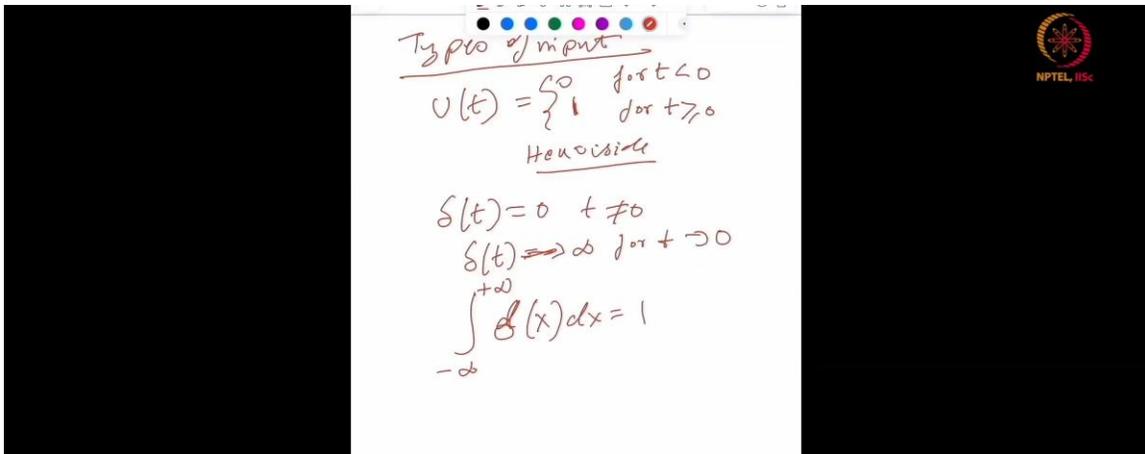→ critically damped
   $\zeta = 1$
→ over damped $1 < \zeta$

We'll see why this will be important because PIV, when we actually do PIV, for example, will show you what kind of systems the particles are. How do they respond to the flow? So, with the exception of zeroth-order systems, the output of all other systems exposed to a time-dependent input depends not only on the current value of the input but also on its time   history.

For the description of dynamic response, it is customary to consider a few idealized types of inputs. So let us consider the types of inputs. Okay, this will come in handy, as I said, when you actually have a relatively fast speed; this can be anything, this can be velocity, this can be anything. So it goes for, say, e less than zero; it was this.
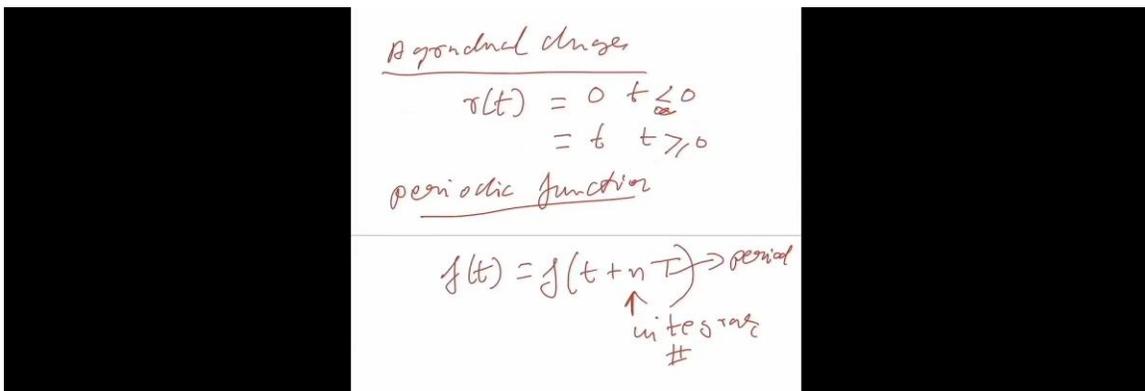
For t greater than or equal to 0, it becomes equal to 1. So it's a relatively fast change in the input from one constant level to another. It is like a unit step function or a Heaviside function. Then a sudden impulse, pulsing application of a different value of the input. Lasting only for a brief time period can also be idealized as a unit impulse function, a Dirac delta   function.

So this is like a Heaviside function. Then you can have situations where your delta t is equal to zero for t less than or equal to zero, delta t approaches infinity for, say, t greater than zero. So the idea is $\int_{-\infty}^{\infty} 1\, \delta(x)\, dx = 1$. So this may be idealized as being proportional. You can have a sudden impulse that lasts for a very small instant before it returns to the original   level.

$$Type\ of\ input$$

$$U(t) = \begin{cases} 0 & for\ t < 0 \\ 1 & for\ t \geqslant 0 \end{cases}$$

Heaviside

$$\delta(t) = 0 \quad t \neq 0$$
$$\delta(t) \Rightarrow \infty \quad for\ t \to 0$$
$$\int_{-\infty}^{+\infty} \delta(x)\,dx = 1$$

You can also have a gradual change. So this is for an impulse. For more gradual change, starting from a constant level and persisting monotonically, say for example, *r(t)* is equal to zero for t less than or equal to zero, then it is equal to t greater than or equal to something like that. You can also have periodic functions. A function can be periodic. So that you can also   have,   say,   a   periodic   function.

Let's write that. Where you know your *f(t)* is basically equal to *f(t + nT)*, where n is an integer. Time period. This is the period, right? So you can see all these nice little features.

A gradual change

$$r(t) = 0 \quad t \leq 0$$
$$= t \quad t \geqslant 0$$

periodic function

$$f(t) = f(t + nT) \Rightarrow period$$
$$\uparrow$$
$$integer$$
$$\#$$

So you can do that, and then you can also now calculate the dynamic response for first-order systems, second-order systems, and stuff like that, which you can read once again from   the   book.

I am giving you a heads up that you can read. There is a lot of material in the book. You should read chapters on step responses. So, you know, the dynamic response, say, of a first-order system, response of first-order systems. So you can have a step response.

You should read this from the book "Step Response." So it's something like $X(t) = AU(t)$. Remember U(t) is the function that we just found. Then you can also have an impulse response. where your $X(t) = A\delta(t)$. And you can now calculate that what will be the dynamic response of the first order systems, how the system will respond to changes like

this.

 And you can also have a ramp response, which is basically monotonic. This is right, which we just did okay, and you can also do this; these will be the kinds of responses. Then you can also go to the responses of the second-order systems, and there you can do the same thing for the step response, dynamic response, impulse response, or ramp response. All these things. And then you can go to higher order and highly nonlinear systems.

 And you can also use things like the Laplace transform. See how these responses, how the time-dependent responses, can be analyzed. So these are kind of what you can read from the book. And there are a lot of things that one can do. But you can also do the same thing here for the second-order systems. There's no time to do the math, but you can try the math, and then you can also go to higher-order systems to see how Laplace transforms and other things   actually   help.

 So we talked about static response, we talked about dynamic response, we talked about what the measurement system is, what the sensors are, how the sensors need to be calibrated, how the sensors can actually work, and how there can be interfering signals from all over. And also, what we did not cover again is something that you should read. You should read about the tests, the data tests, and the curve fits that are part of this particular exercise.
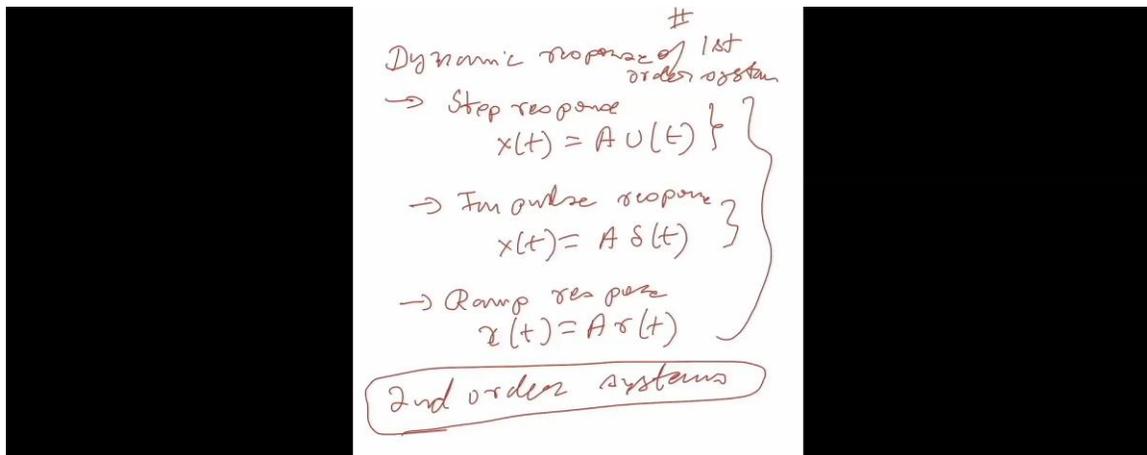
So the book that one should read in this context is "Measurement for this Part: Measurement   in   Fluid   Mechanics.

" Fluid Mechanics by Ravros Kavvalaris. This is a very good book published by Cambridge University Press. I covered the fluids lecture and this lecture from this book. So this is a good start, which you can have and go through. And I've just given you some ideas about the different measurement systems because this dynamic response and other things will be needed once you try to analyze systems, particularly using PIV, even with hot-wire

anemometry. And even if you want to take point measurements, like temperature, using a basic thermocouple, that is also something that you can cover as part of this book.

So, we have covered a lot in fluid mechanics as well as measurement systems. We have also seen how the systems actually respond, even though we did not go into the math part of it. To say okay, there will be a lecture on signal conditioning and image analysis because we are not going to cover all of these things; you are supposed to read up from the book. Okay, that is how, for example, measurement uncertainty, measurement errors, and stuff like that—these are some things that you should learn by reading from this book. Okay, we are going to cover just the image analysis and the signal conditioning part in the later section of this particular course, so we stop here before we move to the measurement techniques. Now, okay, and measure—not measurement—first look at the imaging and the optics part, and then go on to the measurement techniques.