

Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

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Week – 12

Lecture - 59

Hot Wire Anemometry – 3

So the modes are, as we already said, that there is a constant current mode and a constant temperature mode. So in the constant current anemometer, which is also called the CCA anemometer, the current through the sensor is kept constant, which we already said. Okay. The advantages are that it can give you a very high frequency response, but the disadvantages are that these are difficult to use, the output decreases with velocity, and there is a risk of probe burnout. In the case of a constant current anemometer, the current is kept constant, but what happens is that it can actually lead to burnout of the probes, remember, because the temperature is the one that you are kind of measuring in this particular case as the temperature changes. The other one is a constant temperature anemometer or the CTA, so again, you see that this is one part of one leg of the circuit.

Constant current anemometer

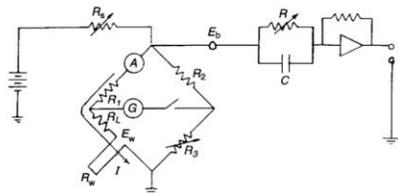
CCA



- Principle:
Current through sensor is kept constant

- Advantages:
 - High frequency response

- Disadvantages:
 - Difficult to use
 - Output decreases with velocity
 - Risk of probe burnout



So the sensor resistance is kept constant by the servo amplifier because the advantages are very easy to use. It has a high frequency response and low noise. It is an accepted standard, but it has a little bit of a complex circuitry. That means the electronics are a

little

bit

complex.

So, essentially, it is a balance of the Wheatstone bridge that actually enables you to measure. In a constant current or constant temperature anemometer, you measure the fluid velocity. For example, this is a pretty complicated three-wire or three-direction anemometer, and there is a three-channel tri-axial wire probe. So this is very complicated; as you can see, there are wires crossing it, you know, all over, so this is a pretty hard configuration, and this requires a lot of calibration and is very difficult to use; also, it is not very easy. So, in the case of a CTA or constant temperature anemometer, the wire resistance we already know is written like this.

Constant temperature anemometer CTA II



- 3-channel StreamLine with Tri-axial wire probe 55P91



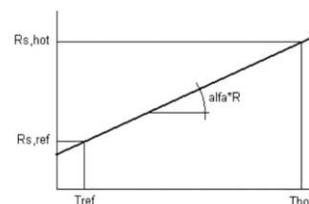
Modes of operation, CTA I



- Wire resistance can be written as:

$$R_w = R_o(1 + \alpha_o(T_w - T_o))$$

R_w = wire hot resistance
 R_o = wire resistance at T_o
 α_o = temp. coeff. of resistance
 T_w = wire temperature
 T_o = reference temperature



- Define: "OVERHEAT RATIO" as:
 $a = (R_w - R_o) / R_o = \alpha_o(T_w - T_o)$
- Set "DECADE" overheat resistor as: $RD = (1 + a)R_w$



Forget about the nomenclature; it's more or less the same. α_0 is the temperature coefficient; R_0 is the resistance of the wire at T_0 . This is what we refer to as R_{ref} or R_{ref} ; they are the same thing. You can define something like an overall heat ratio, which is nothing but $\alpha_0(T_w - T_0)$ and then you can actually calculate it. Remember here, the wire temperature is related to the resistance, and the velocity is therefore dependent on the resistance; that's what it is, right? So the mode of operation that you know when the voltage is across the wire is like this.

This is actually given by the velocity, or R_w is kept constant by the servo loop. So, because you are keeping the R_w constant, E squared is given as $A + BY^n$. Now, therefore, E and U are basically related by this particular expression. So, the response is nonlinear. In CCA, the output decreases.

In the CTA, that is the constant temperature anemometer, the output increases. The sensitivity decreases with increasing values of U . So, this is the kind of graph that you actually get. It's non-linear. The response is nonlinear.

So, therefore, E and U are basically measuring E . So that gives you U . That is what it is. So, what is the dynamic response? So the dynamic response is an important part because the analysis of the wire's dynamic response requires looking at the governing equation, which now includes the term due to thermal energy storage within the wire. So this is the expression.

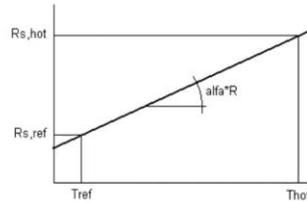
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This equation then becomes a differential equation. As you can see, you are substituting E as basically MCPT or an expression of T_w in terms of R_w . This is the combined expression that you are going to write. Forget about these symbols. You can just work out the math.

It's very simple math. So you are basically substituting everything here. Okay, so you are putting T_w in terms of R_w therefore, you are getting this kind of differential. In the hot wire probe, the first-order differential equation is characterized by a single time constant, which is τ . Thus, the normalized transfer function can be expressed as this.

Dynamic response, CCA II



Hot-wire Probes:

The first-order differential equation is characterised by a single time constant τ :

$$\tau = Cw/(\alpha oPo(A+BY^n))$$

The normalised transfer function can be expressed as:

$$H_{wire}(f) = 1/(1+jff_{cp})$$

Where f_{cp} is the frequency at which the amplitude damping is 3dB (50% amplitude reduction) and the phase lag is 45°.

Frequency limit can be calculated from the time constant:

$$f_{cp} = 1/2\pi\tau$$



Dynamic response, CCA III



• Hot-wire Probes:

Frequency response of film-probes is mainly determined by the thermal properties of the backing material (substrate).

The time constant for film-probes becomes:

$$\tau = (R/R0)^2 F^2 \rho_s C_s k_s / (A+BU^n)^2$$

ρ_s = substrate density

C_s = substrate heat capacity

k_s = substrate heat conductivity

and the normalised transfer function becomes:

$$H_{film}(f) = 1/(1+(jf/f_{cp})^{0.5})$$



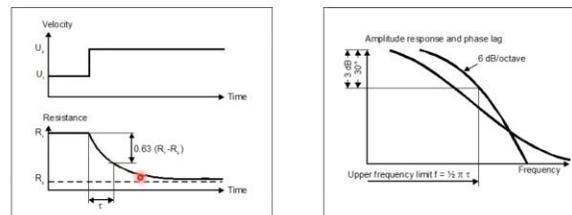
Where f_{cp} is the frequency at which the amplitude damping is about 3 decibels, which corresponds to a 50% amplitude reduction with a phase lag of 45 degrees; this frequency limit can be calculated from this particular time constant, and this is the dynamic response of the hot wire. The frequency response is mainly determined by the thermal properties of the backing materials. So, the time constant of the thermal probe is given by this very complicated expression. Okay, it's not complicated; it's basically a large, messed-up expression. So where ρ_s is a substrate density, this is the substrate heat

capacity, and this is the substrate heat conductivity.

So the normalized transfer function becomes what we showed earlier. So this is the one. OK, so this is the math that you can work out on your own time. And it is kind of a little bit of algebra, so to speak. So what happens is that let's assume you have a step change in velocity with respect to time, because this is what you want to capture.

Right. And what happens to the resistance that this kind of starts to decay? So this was the resistance. When there is a velocity jump, it decays, and with time, it kind of comes down to a new normal, so this decay, where it kind of drops to 63% of its total value, is what is given by this time constant tau. This is how it behaves when the velocity changes; the resistance changes. Not exactly like a step, but more like a decaying function; over tau, it kind of quickly responds and comes to about, you know, 63 percent of its final value. Okay, so there will be a little bit of a phase lag, and then there will be a little bit of a time delay.

Dynamic response, CCA IV



- Dynamic characteristic may be described by the response to
 - Step change in velocity or
 - Sinusoidal velocity variation



So this is the time delay by which the hot wire kind of catches up with the change in flow velocity. So it can be a step change; it could be a sinusoidal change. This is how the response function actually acts, which means how the hot wire responds to this sudden jump in the velocity. The hot wire response is more characterization of the same; this is how the dynamics work for a five micrometer hot wire probe in CCA mode. This time constant is approximately 0.

Dynamic response, CTA I



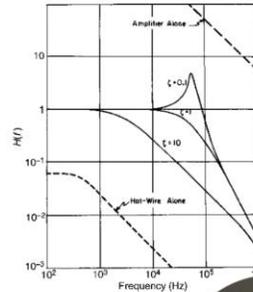
- CTA keeps the wire at constant temperature, hence the effect of thermal inertia is greatly reduced:
Time constant is reduced to

$$\tau_{CTA} = \tau_{CCA} / (2aSRw)$$

where

a = overheat ratio
 S = amplifier gain
 Rw = wire hot resistance

- Frequency limit:
 f_c defined as -3dB amplitude damping



(From Blackwelder 1981)



005 seconds. So typically, this can be improved further, but this is actually a low point. So if you invert it, that is the kind of frequency you are going to get. So in CTA, the CTA, as we know, keeps the wire at a constant temperature. Hence, the effect of the thermal inertia is greatly reduced. So the time constant is also reduced.

So the time constant of the CTA is equal to the time constant of the CCA divided by the overheat ratio, amplifier gain, and a bunch of other parameters. So this is how the dynamic, because this tau is very important. This is the time it takes to basically adjust to step changes in velocity. So it has a lot to do with the circuitry, and a lot of it is proprietary information regarding how people actually implement this. So the typical response of a 5 mm wire probe is kind of given the relative amplitudes.

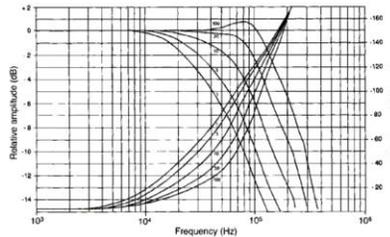
The phase lag is also reduced by frequency-dependent gain, so these are more details that are not part of this course, but if you take hot wire anemometry separately, you should be able to have a good idea of what this is all about. So, the velocity calibration, as we see, despite there being extensive work.

The velocity calibration has no universal expression to describe the heat transfer from the hot wires in the film, so for all actual measurements, the direct calibration of the anemometer is therefore necessary, as there is no universal expression because what we are doing is using a form for the Nusselt number, which is dependent on the flow velocity raised to the power of something. So, how the velocity is determined, this is static calibration. So, for example, you put a probe into a flow field.

Dynamic response, CTA II



- Typical frequency response of 5 mm wire probe (Amplitude damping and Phase lag):



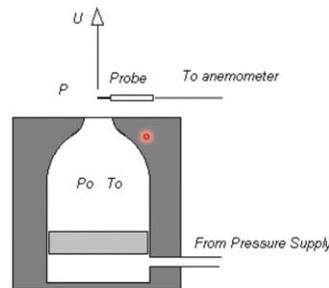
Phase lag is reduced by frequency dependent gain (dB/octave)

Velocity calibration (Static cal.)

II



- Calibration in gases (example low turbulent free jet):



Velocity is determined from isentropic expansion:

$$P/P_0 = (1 + (\gamma - 1)/2 M^2)^\gamma / (\gamma - 1)$$

$$a_0 = (\gamma P T_0)^{0.5}$$

$$a = a_0 / (1 + (\gamma - 1)/2 M^2)^{0.5}$$

$$U = Ma$$

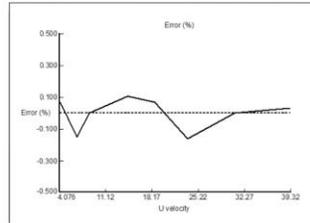
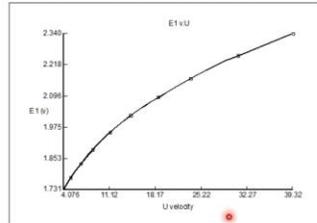


This is, for example, a low-turbulence free jet, and you are putting the probe right over there, and you can determine the velocity, and then you can calibrate the anemometer with respect to that. You can also do it in pipe flows; you can do it in other cases as well. So this is just a calibration that you require to fix what your constants are. So this is, for example, film probes in water. This uses a free jet issuing from the bottom of a container and towing the probe at a known velocity in still water.

Typical calibration curve



- Wire probe calibration with curve fit



(Obtained with Dantec Dynamics' 90H01.02) Calibrator)

Curve fit (velocity U as function of output voltage E):

$$U = C_0 + C_1 E + C_2 E^2 + C_3 E^3 + C_4 E^4$$

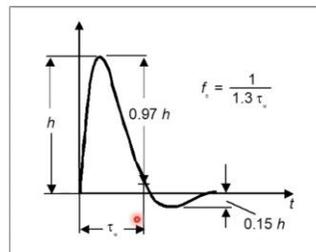


Dynamic calibration/tuning III



- Indirect method
"SQUARE WAVE TEST"

Subject the sensor to an electric sine wave which simulates an instantaneous change in velocity and analyse the shape of the anemometer output



(From Brunn 1995)

For a wire probe (1-order probe response):

Frequency limit (- 3dB damping): $f_c = 1/1.3 \tau$



So this is another way of actually calibrating it. So, a typical calibration curve will look like this. This is the voltage, this is the velocity, and your curve fits you as a function of the voltage. So this is how you fit the calibration curve over a large expected velocity range and the corresponding voltages, and you imagine that you can extrapolate this curve so you can go to higher and higher velocities or lower and lower velocities, and this

curve will still kind of hold, and the error is kept at a very small level; its percentage is about 0.1, so you calibrate it with respect to a known velocity source.

Dynamic calibration



Conclusion:

- Indirect methods are the only ones applicable in practice.
- Sinus test necessary for determination of frequency limit for fiber and film probes.
- Square wave test determines frequency limits for wire probes. Time taken by the anemometer to rebalance itself is used as a measure of its frequency response.
- Square wave test is primarily used for checking dynamic stability of CTA at high velocities.
- Indirect methods cannot simulate effect of thermal boundary layers around sensor (which reduces the frequency response).



Where you know the velocity either analytically or using other equipment, or there is a known closed-form solution, and use that for calibrating this probe. And you can also use low frequency in the low turbulent jets for the same purpose as here. So, dynamic calibration is a little bit of a challenge. So, the direct method is that you need a flow in which there are sinusoidal variations of known amplitude superposed on a mean velocity. So, you have a mean velocity; imagine a pipe flow that has a mean velocity of 10 meters per second, and then you have an oscillating component or a sinusoidal variation on top of that, right? There can be a variety of ways to actually do this.

They are all very restricted to low frequencies as well. So you can use a vibrating probe in a laminar flow. You can also use a microwave simulation, stimulation, and sound well simulation of turbulence. So all you need to do is impose a flow field and see how fast the anemometer actually responds. So there are indirect methods that are also called the sinus test.

Subject the sensor to an electric sine wave that simulates an instantaneous change in velocity, and analyze the amplitude response. So this is another way. So you use an electric sine wave to create the same type of velocity change. So this is artificial, and then

you see the amplitude and how the response is actually working. So, for example, on an amplitude basis, you see up to about 10 frequencies; you don't have a change in the response at all.

Disturbing effects (problem sources)



- Anemometer system makes use of heat transfer from the probe

$$Q_c = Nu \cdot A \cdot (T_w - T_a)$$
$$\bar{Nu} = h \cdot d/k_f = f(Re, Pr, M, Gr, \alpha),$$

- Anything which changes this heat transfer (other than the flow variable being measured) is a “PROBLEM SOURCE!”
- Unsystematic effects (contamination, air bubbles in water, probe vibrations, etc.)
- Systematic effects (ambient temperature changes, solid wall proximity, eddy shedding from cylindrical sensors etc.)



And then this response starts to increase as you go higher in the frequency band. And then there is a sharp drop. So this is a typical wire response that you would normally associate with it. So this is kind of a little on the tough side. I mean this indirect method of sinuous testing is actually where you subject the sensor to an electric sine wave that simulates an instantaneous change in velocity and analyze what the amplitude response is.

So there are also indirect square wave tests. So you subject the sensor to an electric sine wave that simulates an instantaneous change in velocity. And they will analyze the shape of the anemometer's output. And you see what the response time is. And for the wire probe, just so you know, you can also check the frequency limit.

Which is roughly one third, about one point three times the time constant that you have. Okay, one point three times the time constant, that's what it is. Okay, so this is the kind of response that you can actually safely do. So that time constant, as I say, is very important. Okay, so as we saw, it is a function of many things—the time constant.

So the dynamic calibration, the conclusion is the indirect methods are the only one applicable in practice. Sinuous tests are necessary. If you want to determine the

frequency limit for the fiber and the film probes, the square wave test limits determine the frequency limits for wire probes. The time taken by the anemometer to rebalance itself is a measure of its frequency response, right? That means how much time it takes to adjust to the frequency. So, what kind of time it takes there is always a time delay; the shorter the time, the better your frequency response.

The square wave test is primarily used for checking dynamic stability at high velocities because you want to check whether the anemometer is responding properly or not. The indirect methods cannot simulate the effect of thermal boundary layers, for example. Around the sensor, which reduces the frequency response, so it's a very sensitive method, it's a very sensitive thing to begin with, and therefore it is not very easy. So there are a lot of disturbing effects; the anemometer, as I said, is the problem source, so the anemometer makes use of the heat transfer from the probe. Now, anything that changes this heat transfer other than the flow variable is a problem source.

So, there could be unsystematic effects, like air bubbles, and the probe can actually vibrate. It can also have contamination that may actually, you know, increase or decrease the frequency response. There can be systemic effects, such as changes in ambient temperature; it can be close to a wall, and there could be eddy shedding. So it can momentarily come and disturb this velocity because you are dealing with a U, and this velocity may be fast enough that the anemometer will not be able to capture it. So there are a multitude of what we call disturbing influences that are already present in these kinds of anemometers.

So the systemic effects—that is, the ambient temperature changes, the solid wall proximity, eddy shedding, bubbles, contamination, and lots of other things—can actually be problem sources because you want the heat transfer to be determined only by the flow variable and nothing else. So this is a sample of data. This is taken again from Professor Settigen's work. So this is the work of Professor Settigen and Professor Shethoprabho Choudhury. So this shows how a hot film anemometer is used for measuring turbulent intensity and average velocity in a turbulent flow over a disc-shaped bluff body.

So note the nature of the velocity profile. So these are the velocity profiles that it actually measures. So you can see that it measures all kinds of velocities, the mean and the turbulence; this is effectively measured by using this bluff body stabilized flow flame, whatever you call it. This is the flow, okay, where it shows how the flow actually varies with respect to the sample data. So this is just a simple setup that shows what is there in this kind of scenario.

Kind of anemometers. Now, let us look into the inaccuracies that we commonly

encounter in hot-wire anemometer measurements. The reason we get these inaccuracies is that the hot wire anemometer relies on the convective cooling of the probe to estimate the velocity, and this convective cooling rate can be altered by factors other than the velocity field itself. We will look into a few commonly observed scenarios to understand how this occurs. And typically, these inaccuracies or errors are of two kinds. They can be systematic errors or they can be random errors.

Errors in HWA measurement

- Anything that alters the heat transfer rate of the hot wire/film probe other than the fluid flow is an uncertainty source for the measurement
- Types of errors
 - Systematic errors - consistent, repeatable inaccuracies that occur due to biases in the measurement system
 - Random errors - unpredictable variations in the measurement due to random fluctuations
- **Systematic errors**
 - Change in Ambient environment (Temp, RH)
 Many fluid properties such as thermal conductivity (k), density (ρ) and dynamic viscosity (μ) vary with ambient temperature. Changes in these parameter alter the heat transfer rate at the HWA probe and can give us inaccurate readings.

Zhou, 2024

Systematic errors are consistent, repeatable inaccuracies, and they occur due to bias in our measurement system. Whereas random errors are unpredictable variations in the measurements due to random fluctuations. We will look into a few examples again to understand the difference between the two. In systematic errors, the most commonly observed source is due to changes in the ambient environment. As we already discussed, the convective cooling of the hot wire probe is what determines the velocity; that is what is used to determine the velocity in hot wire anemometer measurements.

A change in the ambient can alter the convective heat transfer rate at the probe, and this can lead to inaccurate readings. So, to understand this, let us look at a very simple example. Say we have a hot wire anemometer probe that is calibrated for 20 percent relative humidity, so that corresponds to the black curve that we see over here. Now we are operating in an environment that has 80 percent relative humidity, and the flow field has a true velocity of around 0.5 meters per second, which is the true velocity of the flow field.

Now, if we put this hot wire anemometer probe, which is calibrated for 20 percent relative humidity, into this environment, it would show a reading, an E value of approximately 1.4, that corresponds to this green curve because that curve corresponds to 80 percent relative humidity. But since our probe is actually calibrated for 20 percent relative humidity, it would show that the velocity it measured is approximately 0.55 meters per second, which corresponds to this black curve for the same evaluation. What has effectively happened is that, because there was a change in the relative humidity of the ambient, we have now overestimated our velocity measurement.

If we suppose we are operating in an environment that has a relative humidity of less than 20 percent, basically less than that of the calibration curve, we would be underestimating the velocity. This is a systematic error that we have introduced due to changes in our experiment and the environment of our experimental setup, another commonly encountered source of systematic error. is due to the proximity to the solid wall. To understand this again, let us use a very simple example. Say we have a flat plate in our flow domain, and we want to measure the velocity in the velocity boundary layer that has developed over the plate.

And we are going to use a hot-wire anemometer to measure it. And suppose the plate that we have is a heated plate. The temperature of the plate is much higher compared to the free stream flow. So what happens is that a thermal boundary layer will develop over the plate, similar to the velocity boundary layer. Here, the temperature transitions from the wall temperature to the free stream temperature as we move along this y-axis.

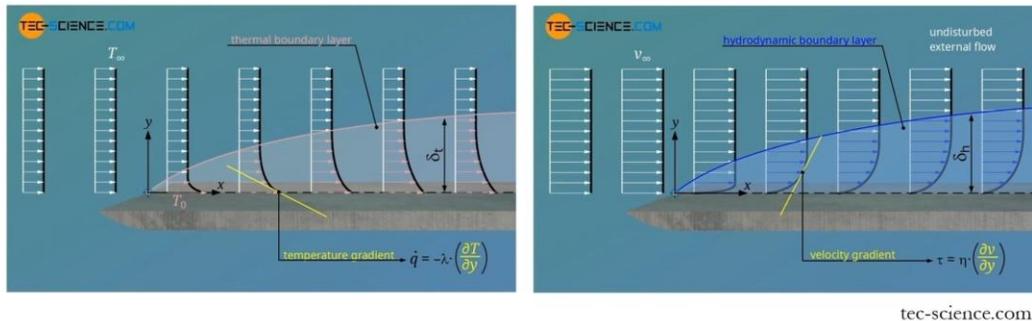
Errors in HWA measurement



○ Systematic errors (cont..)

○ Solid wall proximity

Wall can act as a heat sink or a source, affecting the heat transfer between the sensor and the surrounding fluid. Since the CTA relies on maintaining a constant temperature adjusting the current supplied to the sensor, changes in heat dissipation due to wall proximity can cause inaccurate readings



So this is the thermal boundary layer that we have shown here. Now, if we place our hot-wire anemometer probe inside this thermal boundary layer to measure the velocity, what ends up happening is that the temperature of the local flow interacting with the probe has essentially changed. Now, we are back to the same situation as we saw in the previous slide, where the parameters such as the thermal conductivity, the viscosity, and the density of the ambient air, the ambient fluid that is encountering the probe, have changed. So, now we are operating on a different curve compared to the calibration curve. So, this again leads us to either overestimate or underestimate the velocity measurements depending on whether the plate was actually heated or whether it was a cold plate or in scenarios like this. So again, this is a systematic error because the trends are either to overestimate or underestimate; they are not random in nature.

Flow disturbance due to the hot wire anemometer probe itself is an additional source of systematic errors. A hot wire anemometer probe is basically a bluff body that we introduce into the flow field. And when we introduce a bluff body into the flow field, it essentially distorts and changes the flow field around it. For example, say this is a hot wire anemometer probe that we have inserted into the flow field. And if the flow velocity is such that it exceeds a specific Reynolds number with respect to this probe geometry, it starts shedding vortices downstream of this bluff body.

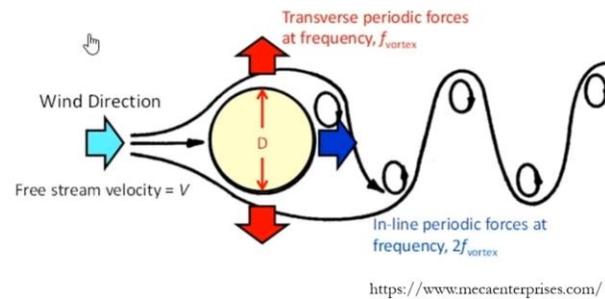
Errors in HWA measurement



○ Systematic errors (cont..)

○ Flow distortion due to sensor geometry

The presence of the probe and the vortices shed from it can distort the local flow field. This distortion affects the flow measurements and introduces systematic errors that are dependent on the probe geometry and flow conditions.



And this vortex shedding trail can effectively alter the velocity even upstream of this probe. So basically, the effective velocity that the probe encounters is different in comparison to the true velocity. So again, this is a systematic error that we have introduced into the system due to the geometry and the size of our probe itself. Additionally, the hot wire anemometer probe that is inserted into a flow field can itself start to oscillate or vibrate in response to the pressure forces and the shear forces it experiences due to the flow field around it. And usually, these oscillations and vibrations have a peak frequency; therefore, the flow distortions that are accompanied by these probe vibrations are also consistent or systematic in nature, and the errors that are usually encountered due to probe vibrations are also systematic in nature.

Now, let us look at the most common sources of random errors. Contamination is the most common source. So, the probe can basically have contamination due to dust, oil particles, or any other particulate matter, and these depositions basically change the heat transfer rate at the probe locally. Therefore, the measurements that we get will also be inaccurate. And since these depositions are random in nature, the error they introduce is also random in nature.

Errors in HWA measurement



- **Systematic errors (cont..)**

- Flow induced probe Vibration

- Flow induced vibration of the probe can change the effective velocity and heat transfer rate at the probe, and can introduce a systematic error in the measurement

- **Random errors**

- Contamination

- Contamination (Eg: dust, oil or particles) deposited on the sensor alters its heat transfer characteristics. These deposits create irregularities on the sensor surface, causing variations in the heat transfer rate between the wire and the fluid.

- Electrical Noise

- Electrical noise can introduce random fluctuations in the measured signal. Electromagnetic interference from nearby equipment and power lines can also add noise to the signal.

The other common source is electrical noise. Since we generally use an amplifier unit or signal conditioning unit to extract data from the hot wire anemometer probe, the components of this circuitry can be affected by electromagnetic interference, and they can introduce additional random noise into our measurement data. Now let us look into the pros and cons of hot wire anemometer systems, especially in comparison with laser-based systems such as particle image velocimetry, which is also used to measure the velocity field. If you look into the pros, first, they are very cost-effective in comparison with PIV systems because PIV systems require us to have a laser system and a high-speed camera system, which are relatively expensive. Whereas here, all we need is a probe, a signal conditioning unit, and a data acquisition unit that is relatively inexpensive. The other important advantage we have here is that we have a very high frequency response.

Errors in HWA measurement



- **Systematic errors (cont..)**

- Flow induced probe Vibration

- Flow induced vibration of the probe can change the effective velocity and heat transfer rate at the probe, and can introduce a systematic error in the measurement

- **Random errors**

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In a PIV system, usually the maximum frequency at which we can operate is usually limited by the frame rate of the camera or the frequency of the laser system. Whereas here, we are limited by the sampling rate of our data acquisition unit. The data that we get from a hot-wire anemometer is usually analog in nature, and the frequency response that we get is only limited by the sampling rate of the data acquisition unit, which is again usually on the order of megahertz, so we get very high temporal resolution. Spatial resolution can also be very high, depending on the diameter of the probe, and today, hardware anemometer probes that are as thin as 10 nanometers are available, so we can get very high spatial resolution as well.

Additionally, the accuracy of hotwire anemometer measurements is very high. The error can be as low as 1%. And the signal-to-noise ratio of 10 to the power of 4 or greater is very typical of hotwire anemometer measurements. And, most importantly, they are very simple to operate in comparison with PIV systems. We do not require any seeding particles. We don't require any control unit between the laser systems and the cameras, which are usually used for PIV measurements.

They are also very compact and portable in nature. Now if we go into the cons of the hotwire anemometer measurements, they require calibration, and we are forced to operate within these calibration limits. As we already saw, going beyond this calibration limit will lead us to inaccurate readings. And also, this is a point measurement technique, unlike PIV, which is a field measurement technique. So, we only get velocity at a

particular point in the flow field, and if we want the velocity in an entire plane, we need to traverse this probe across that entire plane, and that is quite tedious in nature.

Pros and Cons



○ Pros

- Cost (In comparison with laser-based systems)
- Frequency Response (\sim MHz)
- Spatial Resolution ($\sim 10nm$)
- Accuracy (Error $\sim 1\%$)
- Signal to noise ratio (SNR $\sim 10^4$)
- Simple to operate
- No seeding
- Compact

○ Cons

- Requires calibration
- Point measurement technique (Requires traversing to get velocity profiles)
- Intrusive technique (Introduces systematic errors)
- Fragile Sensors

Also, this technique, the hotwire anemometer technique, is intrusive in nature. Basically, that can introduce additional systematic errors that we saw previously. Also, the sensor that is used in hotwire anemometers is very fragile and requires very careful handling. So, overall, a hotwire anemometer has both pros and cons in comparison with PIVs. And they're usually used in different settings. So with that, we have come to the end of the course. Thank you.