Hot-Wire Anemometry

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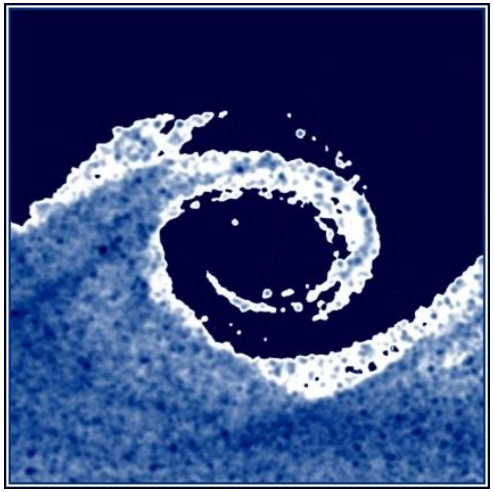
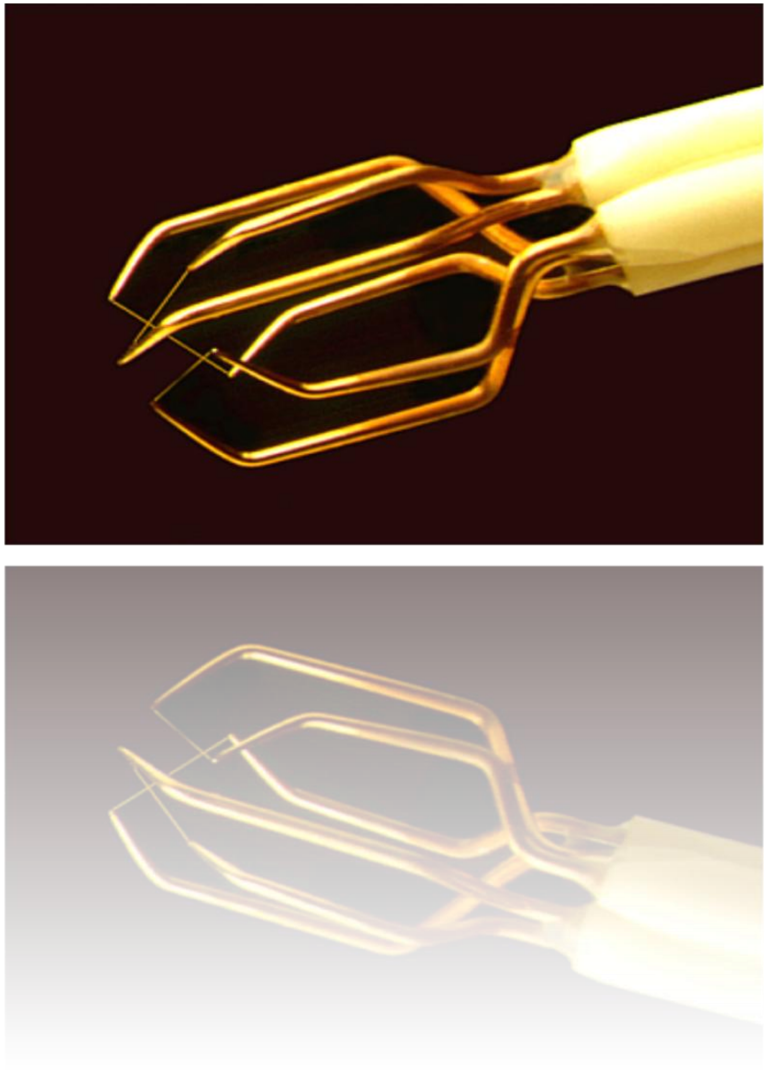




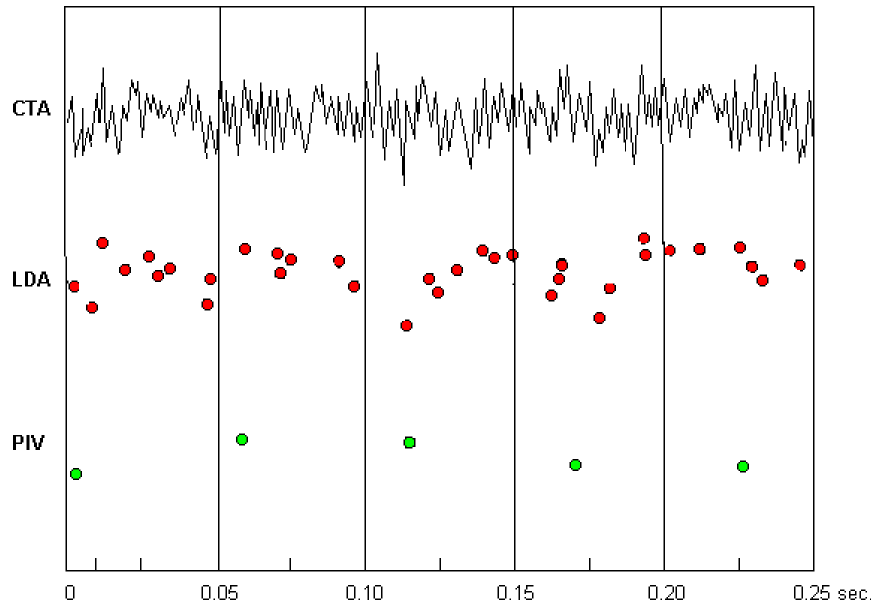
Anemometry

- Anemometry: Measurement of fluid velocity
- What kind of anemometers exist?
- History:
  - Introduced in the first half of the 20th century
  - Commercially available in their present form since the nineteen-fifties
  - Used for measuring the mean and fluctuating variables in fluid flows (velocity, temperature, etc.), with an emphasis on mean velocity and turbulence characteristics
- The measurement technique is based on the heat transfer from a heated wire to the relatively cold surrounding fluid.
  - This heat transfer is a function of the fluid velocity
  - Relationship between the fluid velocity and the electrical output of the system can be established.

Anemometer signal output

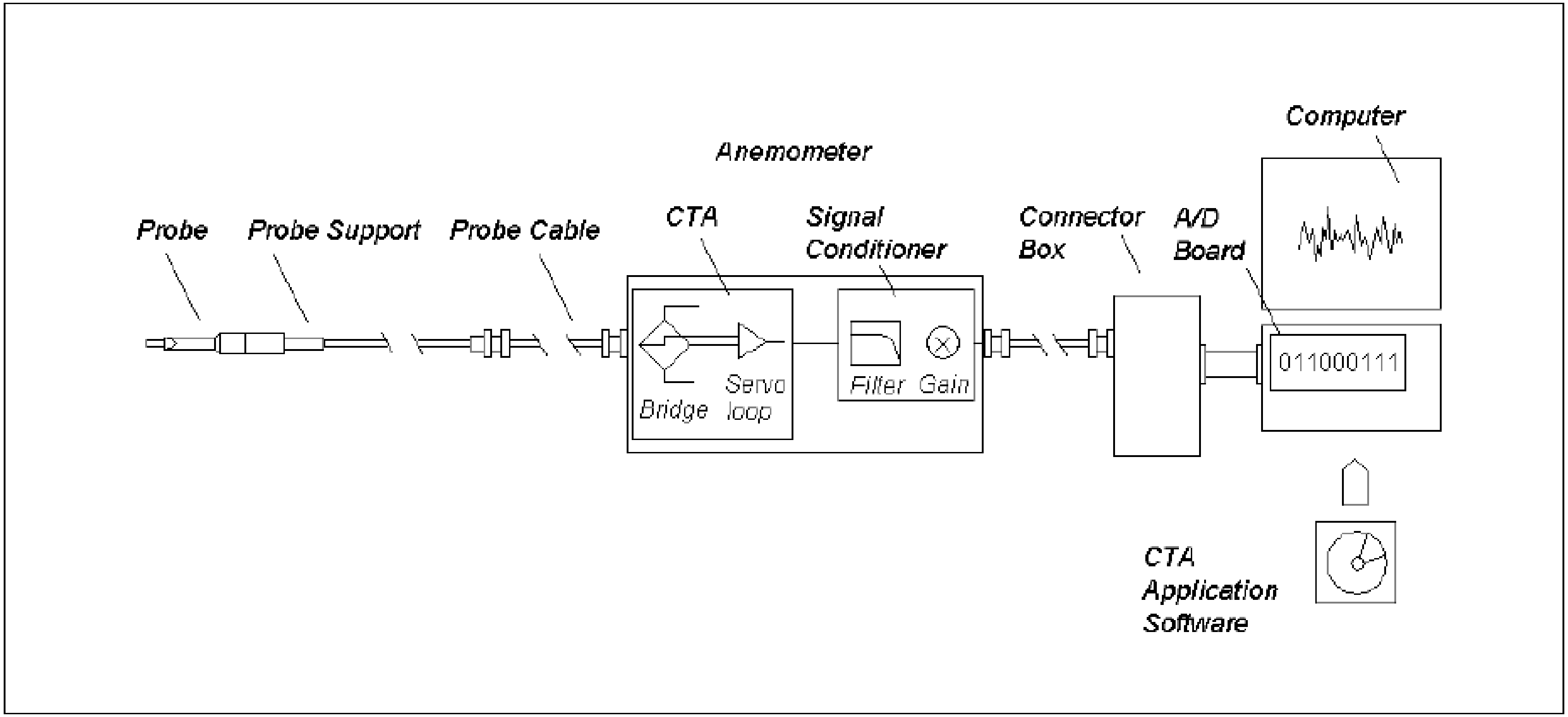
The thermal anemometer provides an analogue output which represents the velocity in a point. Velocity information is thus available anytime.

Note that LDA signals occur at random, while PIV signals are timed with the frame grapping of illuminated particles.



Measurement Chain

- Probe, wire, bridge (Wheatstone bridge for CTA), signal conditioner, D/A convertor, computer, computer program



Probe types I

- Miniature Wire Probes

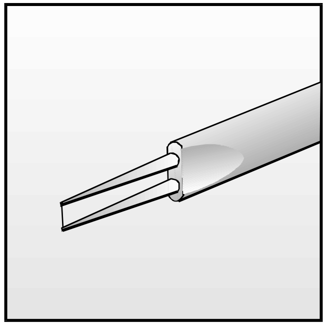
  Platinum-plated tungsten,
  5 μm diameter, 1.2 mm length

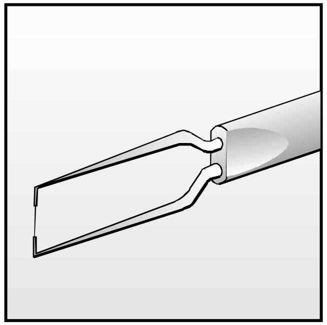
- Gold-Plated Probes

  3 mm total wire length,
  1.25 mm active sensor
  copper ends, gold-plated

Advantages:

- accurately defined sensing length
- reduced heat dissipation by the prongs
- more uniform temperature distribution along wire
- less probe interference to the flow field

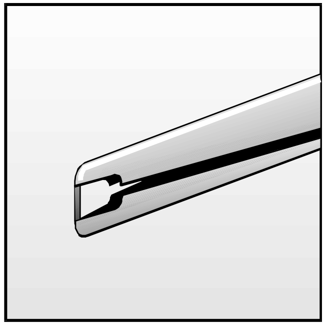




Probe types II

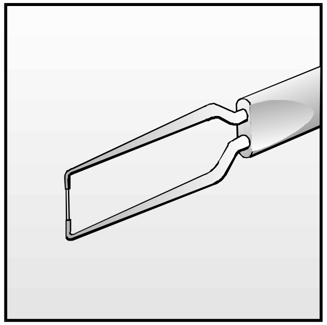
- Film Probes

Thin metal film (nickel) deposited on quartz body. Thin quartz layer protects metal film against corrosion, wear, physical damage, electrical action



- Fiber-Film Probes

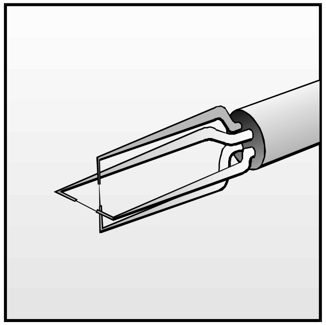
“Hybrid” - film deposited on a thin wire-like quartz rod (fiber) “split fiber-film probes.”



Probe types III

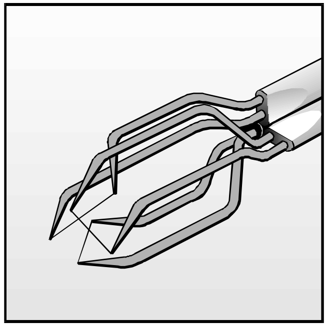
- X-probes for 2D flows

  2 sensors perpendicular to each other. Measures within $\pm 45^{o}$.



- Split-fiber probes for 2D flows

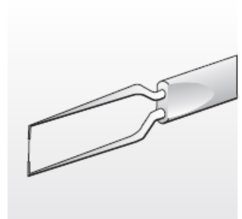
  2 film sensors opposite each other on a quartz cylinder. Measures within $\pm 90^{o}$.

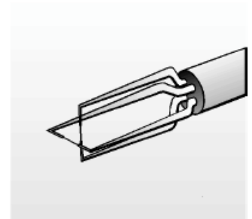


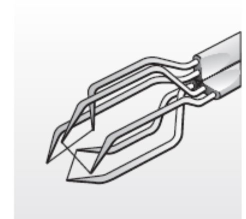
- Tri-axial probes for 3D flows

  3 sensors in an orthogonal system. Measures within 70^{o} cone.

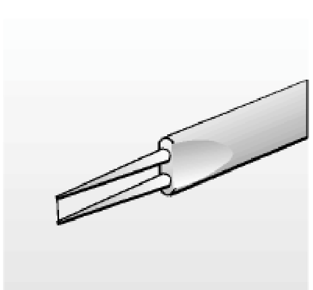
Probe types: advanced I

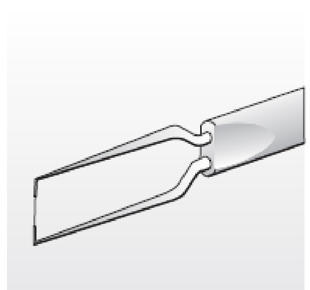


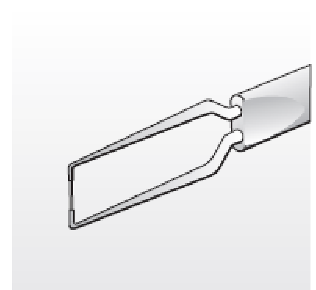


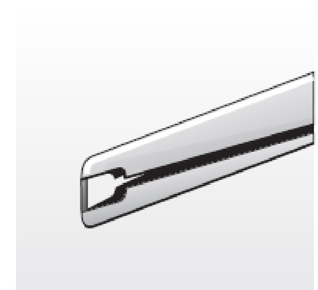


- 1d, 2d, 3d
- Hot-wire, hot-film
- The supports are called prongs, needles or stems
- Wire is the measurement material
- Stubs or wire ends are the parts of the wire near the prongs
- Hot-wire probe (normal and miniature probe)
  - Wire length: 1-3 mm (other source says 0.5-2 mm)
  - Wire diameter is typically 5 μm (between 1-10 μm, other source says 0.5-5 μm)
- Hot-film probe
  - Layer of about 0.1 μm thick deposited of substrate
  - Substrate
    - Fine cylinders of quartz, about 25-50 μm in diameter
    - Quartz wedges
    - Thin acetate or kapton foils.
  - Very thin quartz coating deposited on the sensor provides both protection against a hostile environment and isolation when operating in a conductive medium







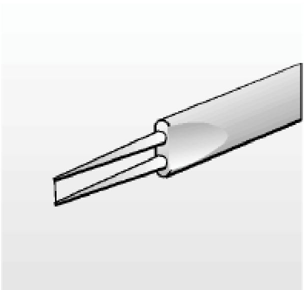
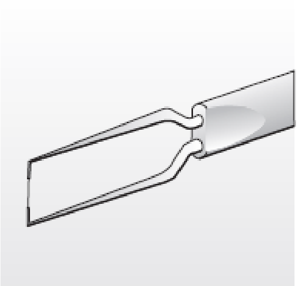
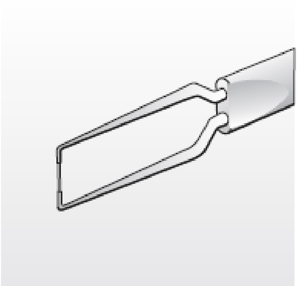
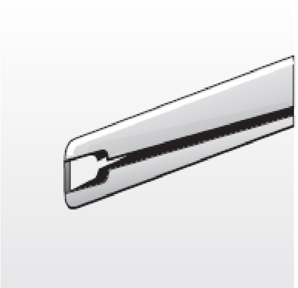


Probe types: advanced 2

- The small dimensions give a small measurement volume
- The material for sensors should have the following properties
  - High value of the temperature coefficient of resistance,
    - Increased sensitivity to velocity variations
  - Electrical resistance such that it can be easily heated with an electrical current at practical voltage and current levels
  - Possibility of being available as wire of very small diameter
  - High enough tensile strength
    - To withstand the aerodynamic stresses at high flow velocities
- Common materials: Tungsten, platinum, platinum-iridium alloys
  - Tungsten:
    - Mechanically strong,
    - High temperature coefficient of resistance (0.004/˚C)
    - Poor resistance to oxidation at high temperatures in many gasses.
    - Most popular
    - When coated with a thin platinum layer, it becomes more resistive to oxidation, changes temperature coefficient to 0.0032/˚C and soldering is eased.
  - Platinum:
    - Good oxidation resistance
    - Good temperature coefficient of resistance (0.003/˚C), mechanically weak (particularly at high temperatures)
  - Platinum-iridium alloy:
    - compromise between the other two
    - Good oxidation resistance
    - Higher tensile strength than platinum
    - Low temperature coefficient of resistance (0.00085/˚C)
  - Platinum-rhodium alloy:
    - Higher temperature coefficient than platinum-iridium
    - Not as strong mechanically as platinum-iridium

Probe types. advanced 3

- Coated wire ends/stubs
  - Gold or copper material
  - Results in better mechanical and aerodynamic properties
  - Reduced heat transfer to the prongs
  - Smaller, better defined measurement length
- Miniaturized hot-wire probes are recommended for low subsonic flows. This helps to make the probes as non-intrusive as possible.
- Film vs. Wire
  - Hot-wire sensors provide superior performance in many applications
  - Hot-film typically has a larger diameter, and therefore a lower spatial resolution
  - In applications requiring maximum frequency response, minimum noise level and very close proximity to a surface, the platinum-coated tungsten hot wire sensor is superior
  - Hot-film is more robust than hot-wire
  - Hot-film is less sensitive to dirt and is easier to clean
  - Hot-film has a more complex material and also a lower frequency response

Probe types: advanced 4

Free and Confined Flows		
Type of flow	**Medium**	**Recommended Probes**
1-Dimensional		
Uni-directional	Gas	Single sensor Wire Single sensor Fiber, thin coat. Wedge-shaped Film, thin coat. Conical Film, thin coat.
	Liquid	Single sensor Fiber, heavy coat. Wedge-shaped Film, heavy coat. Conical Film, heavy coat.
Bi-directional	Gas	Split-fibers, thin coat.
	Liquid	Split-fibers, heavy coat.
2-Dimensional		
One Quadrant	Gas	X-array Wires X-array Fibers, thin coat. V-wedge Film, thin coat.
	Liquids	X-array Fibers, heavy coat. V-wedge Film, heavy coat.
Half Plane	Gas	Split-fibers, thin coat.
	Liquids	Split-fibers, heavy coat.
Full Plane	Gas	Triple-split Fibers, thin coat. X-array Wire, flying hot-wire
	Liquids	Triple-split Fibers, *special*
3-Dimensional		
One Octant (70° Cone)	Gas	Tri-axial Wire Tri-axial Fiber, thin coat.
	Liquids	Tri-axial Fiber, *Special*
90° Cone	Gas	Slanted Wire, rotated probe
	Liquids	Slanted Fiber, heavy coat.
Full Space	Gas	Omnidirectional Film
Wall Flows (Shear Stress)		
Type of flow	**Medium**	**Recommended Probes**
1-Dimensional		
Unidirectional	Gas	Flush-mounting Film, thin coat. Glue-on Film, thin coat.
	Liquids	Flush-mounting Film, heavy coat. Glue-on Film, *special*

Bridge: circuitry

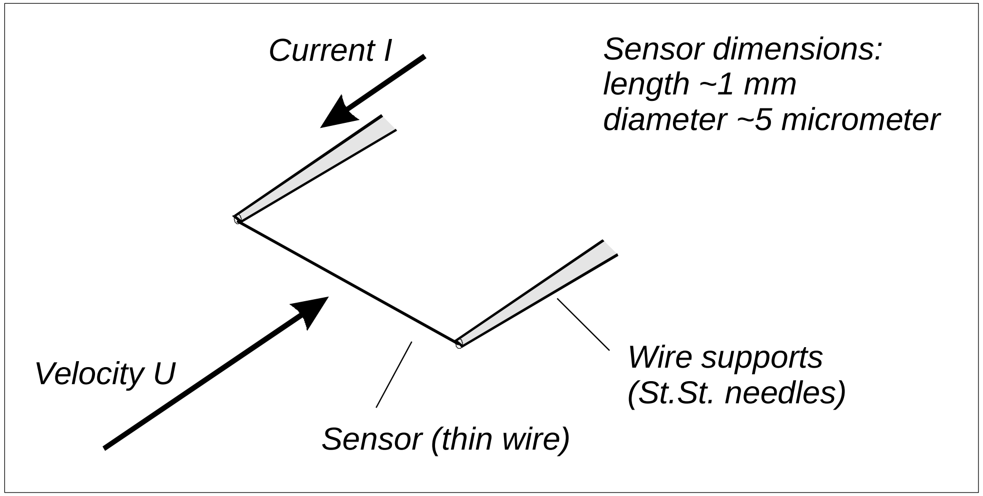
- Provides the wire a controlled amount of electric current

Operation Principle

- Consider a thin wire mounted to supports and exposed to a velocity *U*.

  When a current is passed through wire, heat is generated (I^2R_w). In equilibrium, this must be balanced by heat loss (primarily convective) to the surroundings.

- If velocity changes, convective heat transfer coefficient will change, wire temperature will change and eventually reach a new equilibrium.



Governing equation

- Governing Equation:

$$\frac{dE}{dt} = W - H$$

E = thermal energy stored in wire

$E = CwTw$

Cw = heat capacity of wire

W = power generated by Joule heating

$W = I^2 Rw$

recall $Rw = Rw(Tw)$

H = heat transferred to surroundings

Simplified static analysis I

- For equilibrium conditions the heat storage is zero:

$$\frac{dE}{dt} = O \quad \therefore W = H$$

and the Joule heating W equals the convective heat transfer H

- Assumptions

- Radiation losses small
- Conduction to wire supports small
- *Tw* uniform over length of sensor
- Velocity impinges normally on wire, and is uniform over its entire length, and also small compared to sonic speed.
- Fluid temperature and density are constant

Simplified static analysis II

Static heat transfer:

$$W = H \Longrightarrow I^2Rw = hA(Tw - Ta) \Longrightarrow I^2Rw = Nukf/dA(Tw - Ta)$$

h = film coefficient of heat transfer
A = heat transfer area
d = wire diameter
kf = heat conductivity of fluid
Nu = dimensionless heat transfer coefficient

Forced convection regime, i.e. $Re > Gr^{1/3}$ (0.02 in air) and $Re<140$ $\Longrightarrow$

$$Nu = A_1 + B_1 \cdot Re^n = A_2 + B_2 \cdot U^n$$

$$I^2Rw^2 = E^2 = (Tw - Ta)(A + B \cdot U^n)$$ "King's law"

The voltage drop is used as a measure of velocity $\Rightarrow$ data acquisition, processing

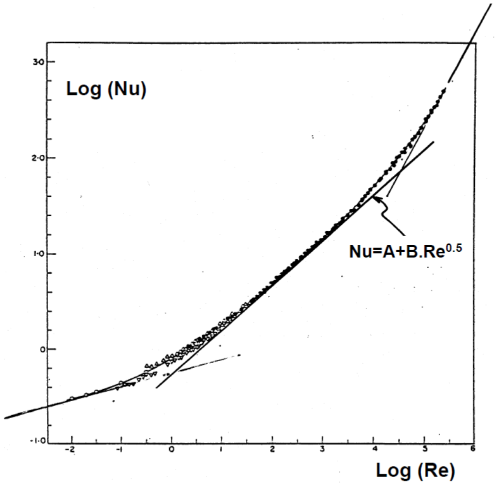
A, B, n: BY CALIBRATION

Advanced Operation Principle I

- Supply= I^2R_w= $\pi Dlh(T_w - T_a)$= Dissipation
  - I= heating current flowing in the wire [A]
  - R_w= resistance in the wire at the operating temperature [Ω]
  - D= diameter of the wire [m]
  - l= length of wire [m]
  - h= heat transfer coefficient [W/(m^{2}K)]
  - T_w= wire temperature [˚c]
  - T_a= fluid (air) temperature [˚c]
- The Nusselt number is a dimensionless number relating the convective and the conductive heat transfer across (normal to) the boundary:
  - Nu= Convective heat transfer coefficient/Conductive heat transfer coefficient
  - Nu= hD/k
- $I^2R_w = \pi lk(T_w - T_a)Nu$
- $I^2R_w = |A+BU^n|(T_w - T_a)$
  - A= represents the natural convection term
  - BU^n= represents the forced convection term
  - U= flow velocity [m/s]

Advanced Operation Principle II

- If one wants to increase the resolution of the measurements, the influence of the natural convection term should be minimized.
- Good working conditions are reached when:
  - $(l/D)(Gr^{1/2})<1$ (or alternatively, $Re> Gr^{1/3}$)
    - Gr being the Grashof number
    - $Gr= (g(T_w - T_a)D^3)/(T_m\, v^2)$
- The resistance of a wire is a function of its temperature.
  - For a metallic conductor: $R_w= R_a[1+b_1(T_w-T_a)+b_2(T_w-T_a)^2+\ldots]$.
  - This can be linearized for a temperature range of up to 200˚c
    - $R_w= R_a[1+b_1(T_w-T_a)]$
  - This results in the following expression:
    - $b_1(I^2R_wR_a)/(R_w-R_a)=A+BU^n$



- Thus the actual value of the heat transfer could be obtained either as…
  - … the value of R_w if I is kept constant. Constant Current Anemometry method
  - … the value of I if R_w is kept constant. Constant Temperature Anemometry method
- Since the frequency response of the the sensors are mostly flat (linear) in a large range (order of 100 Hz- order of 10000 Hz)
  - This allows the instantaneous response of the hot-wire to be written, even for unsteady flows, in an algebraic form as :
    - $E^2=A+B(U)^n$. King's law
    - $E^2=A+BU^n+CU$: Gaulier's modified law
    - $U=k_1+k_2E+k_3E^2+k_4E^3+\ldots+k_{i+1}E^i$: polynomial fit

Advanced Operation Principle III

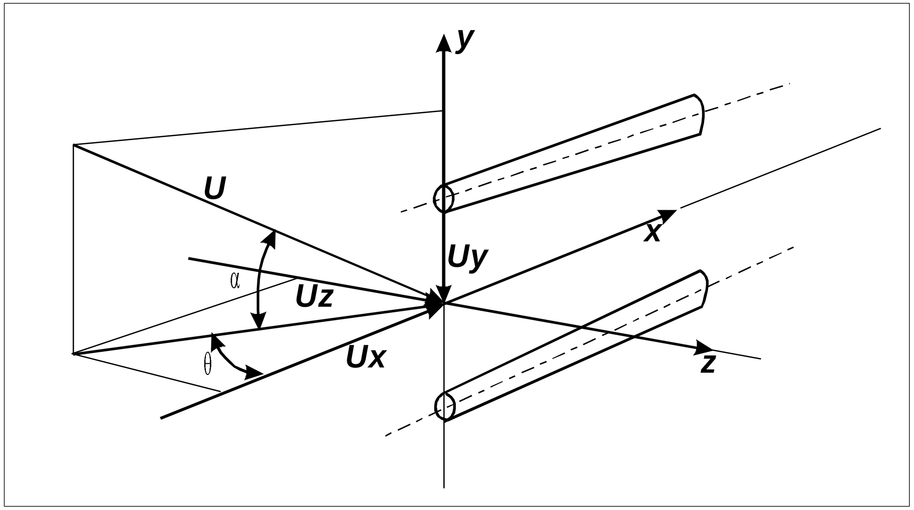
- Control circuits
  - The main difference between the operating modes is linked to the handling of thermal inertia of the sensor.
  - In usual applications, the frequencies of the flow fluctuations to be measured are much higher than the natural frequency of the sensor
  - Therefore electronic compensation is needed
  - In a CCA and CVA, this is achieved by a first-order high-pass filter integrated in the amplifying unit.
    - In a typical CCA application, the filter’s response is tuned to compensate exactly the thermal lag of the sensor. The overall bandwidth is then only limited by the amplifier’s characterisitics, mainly its gain-bandwidth product.
    - With a CVA, the thermal ld is partially compensated during measurements and is fully compensated when post-processing the data. This permits high productivity for large-bandwidth applications because no adjustment is required when the experiment is running.
    - In a CTA, the temperature of the sensor is maintained constant by a feedback loop, so that its thermal inertia is, in principle, automatically compensated. In this case, the maximum bandwidth is limited by the amplifier’s properties and some characteristics of the practical setup. Full compensation can be made after carefully tuning the circuit.

Advanced Operation Principle IV

- Constant current anemometry (CCA):
  - In its basic form, the control circuit may be reduced to a source of constant current feeding a calibration and measurement bridge.
  - The two resistors are chosen to be equal and the value of R is chosen to be equal to the hot resistance of the wire (usually 1.8 times the cold wire resistance) and the supply current is increased until, for zero wind velocity, a balance is obtained at the bridge output.
  - Any change in wind velocity will change the heat transfer, and thus the wire temperature and resistance and cause an unbalanced voltage to appear at the bridge output.
  - This can be calibrated against flow velocity to obtain the wire calibration curve.
  - Has a slow frequency response due to the circuits own thermal inertia.
  - R_w =const., I =I(U)
- Constant temperature anemometry (CTA):
  - The output from the bridge is amplified and used to control the supply voltage such as to maintain the wire temperature constant.
  - The amplifier output E, required to maintain the wire at a constant temperature is a function of the flow velocity.
  - The temperature is again fixed by the choice of the resistance R of the bridge (usually 1.8 times the cold wire resistance).
  - All coefficients can be considered constants.
  - Because the changes in temperature are now much smaller, the thermal inertia of the wire can be expected to play a minor role in determining the frequency response.
  - Because the temperature of the wire remains almost constant, all nonlinearities introduced by the thermal lag effect are substantially smaller and in most cases negligible.
  - The new frequencies to be considered are so high that the reactive phenomena taking place in the wire connection cables and in the amplifier must be taken into account and these increase the order of the response equation.
  - Accounting for a change in T_a, the temperature of the measured fluid, is important.
  - I =const. , $R_w = R_w(U)$
- Constant voltage anemometry (CVA) (new)

Directional response

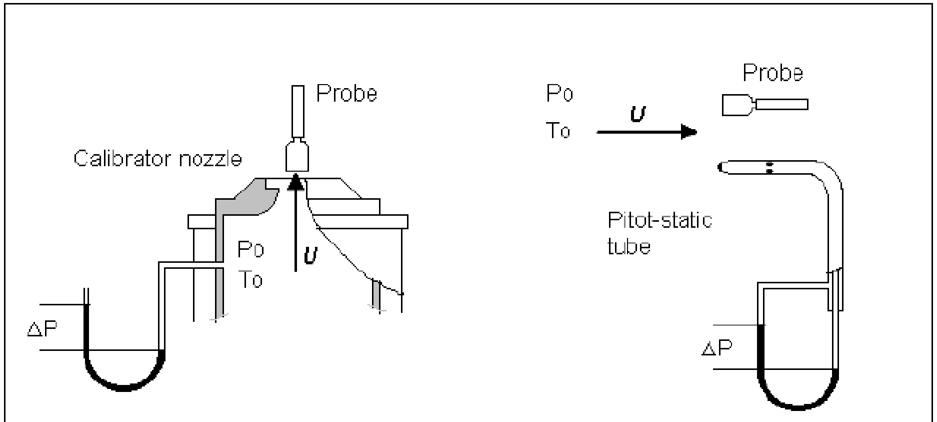
Probe coordinate system



Velocity vector *U* is decomposed into normal *Ux*, tangential *Uy* and binormal *Uz* components.

Calibration

- Velocity calibration:
  - Velocity calibration range: $0.1*U_{min}$ ->$1.5*U_{max}$
  - Need to calibrate the system for the flow angles in case of a multi-component probe
    - Done within the range of the acceptable measuring angle
- Dynamic bridge balancing:
  - Square wave test
    - A square wave is given at the wire terminal and the response of the system is monitored on an oscilloscope
  - Balance the system
  - Therefore optimizing the combined sensor/anemometer circuit to receive the best possible bandwidth (best frequency response and therefore highest possible frequency measurement) or limiting frequency
  - Since frequency response is a function of the fluid velocity…
    - Done at the mean flow velocity at which the probe is likely to operate
    - In case of impulsive flows, done at the mean value of velocity



Advantages and disadvantages I

- Advantages of hot-wire anemometers:
  - Cost is relatively cheap
  - Frequency response is high
  - Size: small measurement volume
  - Good spatial and temporal resolution
  - Turbulent flows can easily be measured with it
  - Multi-component measurement
  - Simultaneous temperature measurement: available with multi-sensor probe
  - Two-phase flow measurement is possible
  - Accuracy is as good as a Laser Doppler anemometer
  - Signal-to-noise ratio is low
  - Probe and analysis selection: It is easy to find a good measurement system for most measurements
  - Signal analysis: Analogue output provides an opportunity for conditionally-sampled time-domain and frequency-domain analysis
  - Spatial separation: Multi-component probes allow for the measurement of multi-component flows
  - Special probes can easily be made
  - Measurements can be made in gases , transparent, opaque, and even electrically conducting liquids.
  - Can measure instantaneous wall shear stresses with wall sensors mounted flush to the surface

Advantages and disadvantages II

- Hot-wire anemometer problems
  - High turbulence intensity
    - Restricted to low and moderate turbulence intensity flows
    - Flow disturbance from outside the measurement plane alters results
  - Liquid flows
    - Can contaminate the probe more easily
    - Temperature changes in the fluid effect the results more due to the smaller overheat ratio which is used in liquids
  - Probe breakage
  - Contamination
  - Intrusive method
  - Heat transfer between the probe and surfaces or the support prongs
  - Noise in the signal
    - Radio frequency signal noise
    - Circuitry noise
  - Heat transfer problems
    - Supports are not as hot as the sensor, due to their larger mass. They act as heat sinks. Therefore the edge of the wire is cooled, reducing the active wire length. This can be accounted for by calibration, and is less of an issue in CTA then in CCA.
    - Thermal wake from one wire could effect the measurements on another probe for a multi-component hot-wire probe.
    - The wires are sensitive to both temperature and velocity, and therefore if both change simultaneously, then the results are contaminated. (Ex. Geophysical flows, high subsonic and transonic flows.)
  - Aerodynamic problems
    - Probes are not sensitive to flow direction (reverse flow)
    - Probe supports interfere with the flow onto the other sensors (multi-component probes, multi-probe arrangements (such as for space correlation measurements))

Etc

- Traverse system
- Software
- Calibration system
- Applications
- Turbulence properties