



A practical guide to turbulence and flow measurement by thermal anemometry (CTA), laser-Doppler anemometry (LDA) and particle-image velocimetry (PIV)

Part 2: constant-temperature anemometry

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A PRACTICAL GUIDE TO TURBULENCE AND FLOW MEASUREMENT BY THERMAL ANEMOMETRY (CTA), LASER-DOPPLER ANEMOMETRY (LDA) AND PARTICLE-IMAGE VELOCIMETRY (PIV)

Part 2: constant-temperature anemometry

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Part 2: constant-temperature anemometry

1. INTRODUCTION

Reference 1 should be consulted before the decision is made to perform flow measurements using thermal anemometry, typically a constant temperature (CTA) anemometer. A brief description of the basic principles of the CTA is also given in this reference but, for convenience a more complete account is given here.

CTA anemometry is an invasive technique that works on the principle of convective heat transfer from a heated sensor (wire or film) to the surrounding fluid. This transfer of heat is primarily a function of the fluid flow over the sensor. Various sensors are used but the most common are fine wires (typically 5 μm in diameter) or thin nickel films on quartz substrates. These sensors are mounted in a Wheatstone bridge circuit supplied by a high-gain servo loop, which enables the measurement of velocity fluctuations to a very high temporal and spatial resolution.

The principle benefits of this technique are:

- high temporal resolution- some high grade CTA anemometers have frequency responses in excess of 100 kHz,
- high spatial resolution- typical hot-wire probes have an active wire length of 1.25mm and diameter of 5 μm ,
- Interference with the flow is slight as the probes are small,
- ease of use,
- analog output with no data loss-this is an ideal tool for measuring spectra,
- relatively low cost compared to non-invasive optical techniques.

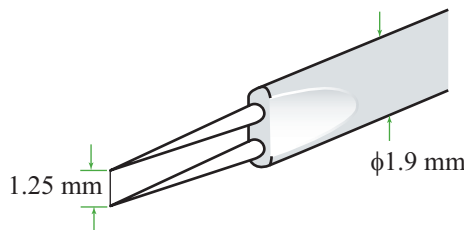


**FIGURE 1.1 Hot wire probe (5 μm plated tungsten wire welded to the prongs)
(Courtesy DANTEC Dynamics)**

There are a number of CTA probe configurations but the most common consists of a thin wire (Figure 1.1) mounted between two supports and exposed to a fluid stream. When a current is passed through the wire, thermal energy is generated at a rate equal to the square of the current times the resistance of the wire. To maintain equilibrium this must be balanced by heat loss (primarily convective) to the surroundings.

If the velocity changes, the rate of convective heat transfer from the wire will be altered and the heating current required to maintain the wire at a constant temperature will also change. This current is thus a measure of flow velocity and, after calibration, a CTA can be used to measure:

- velocity,
- turbulence intensity,
- higher order statistical moments such as stress terms,
- transition from laminar to turbulent boundary-layer conditions.

2. NOTATION

a	probe overheat ratio
B	constant in King's law (Equation (7.1))
B_R	bridge ratio ($= R_{t2}/R_{t1}$)
d	sensor diameter
E_{corr}	corrected anemometer output (Equation (8.1))
E_{RMS}	root mean square value of E
E	anemometer output
E_0	anemometer output with zero flow
$\bar{E}$	time averaged anemometer output
f_c	frequency at which amplitude is damped by a factor of 2 (Equation (4.6))
f_{hp}	high-pass filter cutoff frequency
h	directional calibration constant relating to u_z (Equation (3.2))
h_p	maximum value in anemometer response curve (Figure 4.6)
k	directional calibration constant relating to u_y (Equation (3.1))
n	constant in King's law (Equation (7.1))
L	sensor length
R_c	probe cable resistance
R_{ptot}	total resistance in probe bridge arm under running conditions (Equation (4.1))
R_{t1}	resistance in top bridge arm (Figure 4.4)
R_{t2}	resistance in top bridge arm (Figure 4.4)
R_s	probe support resistance
R_v	variable resistance in lower bridge arm (Figure 4.4)
R_w	sensor resistance under running conditions
R_0	sensor resistance at reference temperature, T_0
T	temperature
T_c	ambient fluid temperature at which the probe is calibrated

T_w	operating probe temperature
T_0	reference temperature at which sensor resistance is R_0
T_{oc}	ambient temperature of fluid during calibration
T_{of}	ambient temperature of fluid under operating conditions
t	time
t_{rec}	time over which a data sample is recorded
U	fluid velocity at probe
U_{RMS}	root mean square value of $\bar{U}$
U_{eff}	effective cooling velocity
U_{eff1}	effective cooling velocity for wire 1 in cross-wire probe
U_{eff2}	effective cooling velocity for wire 2 in cross-wire probe
U_{max}	maximum value of U anticipated in a test
U_{min}	minimum value of U anticipated in a test
$\bar{U}$	time averaged velocity
u_x	velocity component in x direction
u_y	velocity component in y direction
u_z	velocity component in z direction
x	direction of probe axis (Figure 1.1)
y	direction normal to probe axis and aligned with sensor (Figure 1.1)
z	direction normal to both probe axis and sensor (Figure 1.1)
α	flow direction relative to probe (Figure 1.1)
α_T	rate of change of probe resistance with temperature
ΔE	small change in E
ΔU	small change in U
θ	flow direction relative to probe (Figure 1.1)
θ_{turn}	angle at which calibration turntable is set
τ_w	probe response time constant (Figure 4.6)

3. VELOCITY MEASUREMENT

Velocity measurement is possible because misalignment between the velocity vector, U , and the x axis (Figure 3.1) can be allowed for by suitable calibration.

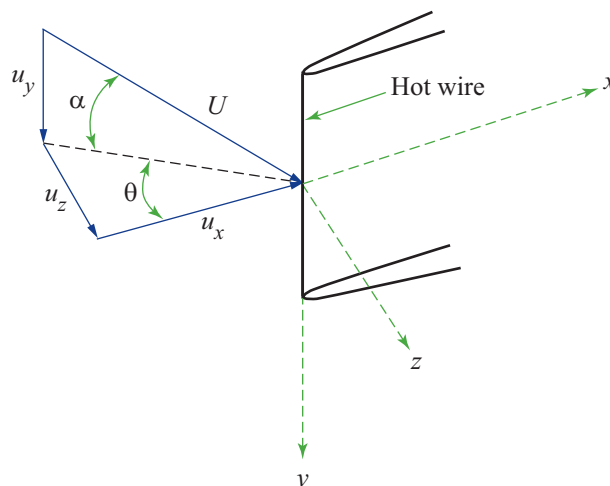


FIGURE 3.1 Velocity components

Consider the case in which, $\theta = 0$. In this case cooling is mainly effected by $u_x^2 (= U^2 \cos^2 \alpha)$ but is also influenced by the square of velocity component in the y direction, *i.e.* $u_y^2 (= U^2 \sin^2 \theta)$, which increases the cooling rate. If U_{eff} (the effective cooling velocity) corresponds to the velocity deduced from the CTA output according to a calibration made with U aligned with the x axis, then, because of the additional cooling due to u_y^2 , U_{eff} will give an overestimate of $U \cos \alpha$, which can be expressed as

$$U_{eff\theta=0}^2 = U^2 [\cos^2 \alpha + k^2 \sin^2 \alpha] = u_x^2 + k^2 u_y^2 \quad (3.1)$$

where $k^2 \sin^2 \alpha$ is the additional term due to u_y .

Similarly, for the case with $\alpha = 0$,

$$U_{eff\alpha=0}^2 = U^2 [\cos^2 \theta + h^2 \sin^2 \theta] = u_x^2 + h^2 u_z^2. \quad (3.2)$$

Following a basic calibration with U aligned with the x axis, the factors h and k can be obtained from further calibrations in which α and θ are varied at constant U .

h and k are respectively known as the pitch and yaw directional-sensitivity coefficients.

Because u_z is normal to the sensor it has a much greater effect on heat transfer than u_y , which is aligned with the sensor. Thus h is much greater than k (*e.g.* typical values for a hot-wire probe in air are: $h = 1.04$ and $k = 0.0225$).

Where both α and θ are non-zero,

$$U_{eff}^2 = u_x^2 + k^2 u_y^2 + h^2 u_z^2. \quad (3.3)$$

When orientation of the probe to the local velocity vector U is not known, since k and h are known from calibration, all three local velocity components can be determined by testing using three different probe orientations at a given point in the flow. Cross-wire and triple-wire probes (Figure 4.3) can be used to resolve two- and three-component time histories. Time-averaged quantities can be determined using a single-sensor probe, the orientation of which can be varied with respect to the local flow direction. The calibration and use of probes to determine individual velocity components is discussed in detail in Section 7.

4. SYSTEM COMPONENTS

A typical system (Figure 4.1) comprises the following elements:

- a hot wire or hot film to respond to the flow,
- a Wheatstone bridge circuit with feedback via a servo amplifier to condition the sensor and convert the heat transfer response of the sensor into a voltage,
- an A-D converter to digitize the signal for analysis in a computer,
- software to calibrate and linearise the anemometer signal,
- software to process statistical quantities, time series, profiles and power spectra.

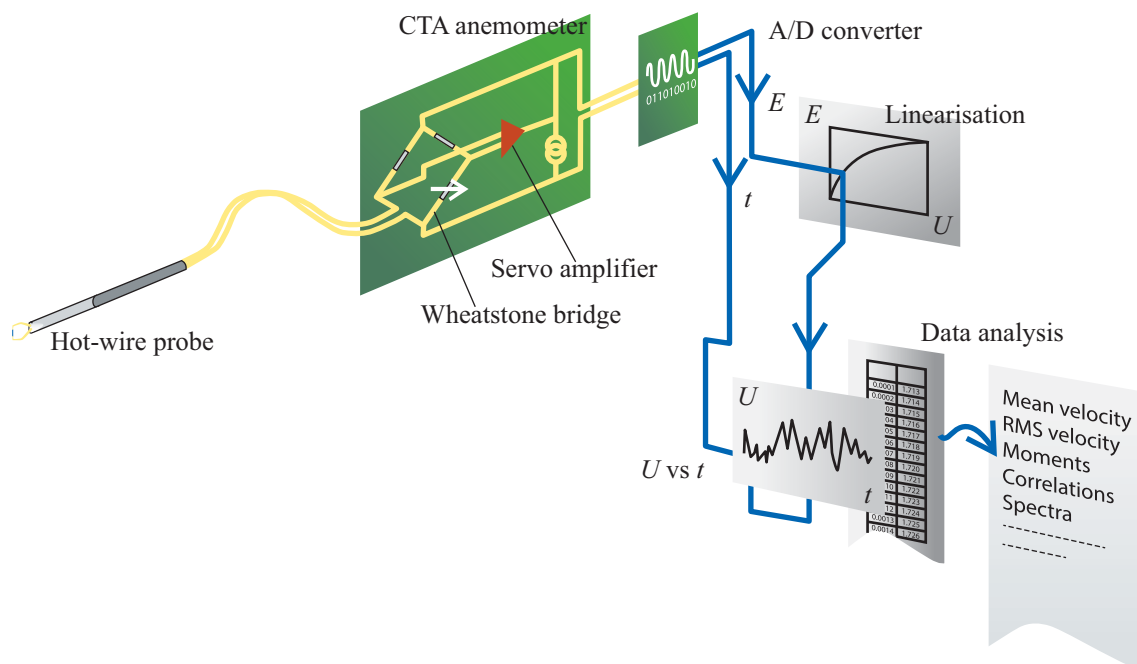
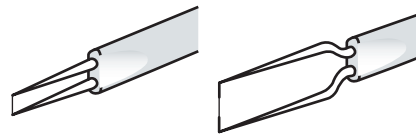
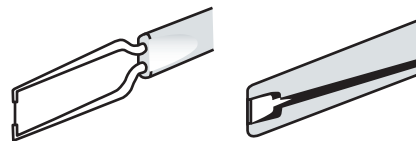


FIGURE 4.1 Components of a CTA system

4.1 Typical Probes



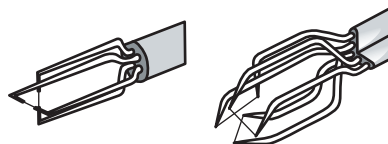
(a) Hot wire probes



(b) Hot film probes

FIGURE 4.2 Typical single-sensor probes

The sensors shown in Figure 4.2 are typical single sensor probes. Figure 4.2a shows the most widely used wire probes for flow and turbulence measurements. The gold-plated probe (on the right) is ideal for high-turbulence measurements as the effect of the prongs is reduced because only the central section of the sensor is active. Figure 4.2b shows a fibre film probe and wedge film probe. The development of these sensors was primarily for high speed flows where wire probes do not survive if the flow is contaminated. They also feature an insulating layer of quartz over the sensor which, if thick enough, will enable the probe to be used in electrically conducting fluids, *e.g.* water. The ceramic body of a wire and fibre probe is typically of the order of 1 mm diameter and the wire sensors are 5 μm in diameter. A fibre probe has a sensor diameter of 70 μm .



(a) Cross-wire (b) Triple-wire

FIGURE 4.3 Multi-sensor probes

The probes shown in Figure 4.3 are examples of cross (x) and triple-wire probes which will, with calibration, enable resolution of the flow in 2 or 3 dimensions respectively.

4.2 Constant Temperature Anemometry Circuit

Figure 4.4 shows a probe (sensor) in a typical CTA circuit. The sensor is mounted as one arm of a Wheatstone bridge to which feedback is provided by a high-gain servo amplifier responding to the error voltage generated by the bridge. The current through the bridge is therefore varied in such a way that the error voltage is minimized, thus maintaining the temperature of the probe at a nearly constant value. This current (and hence the bridge voltage) is dependent on the cooling rate of the probe and is therefore directly dependent on U_{eff} .