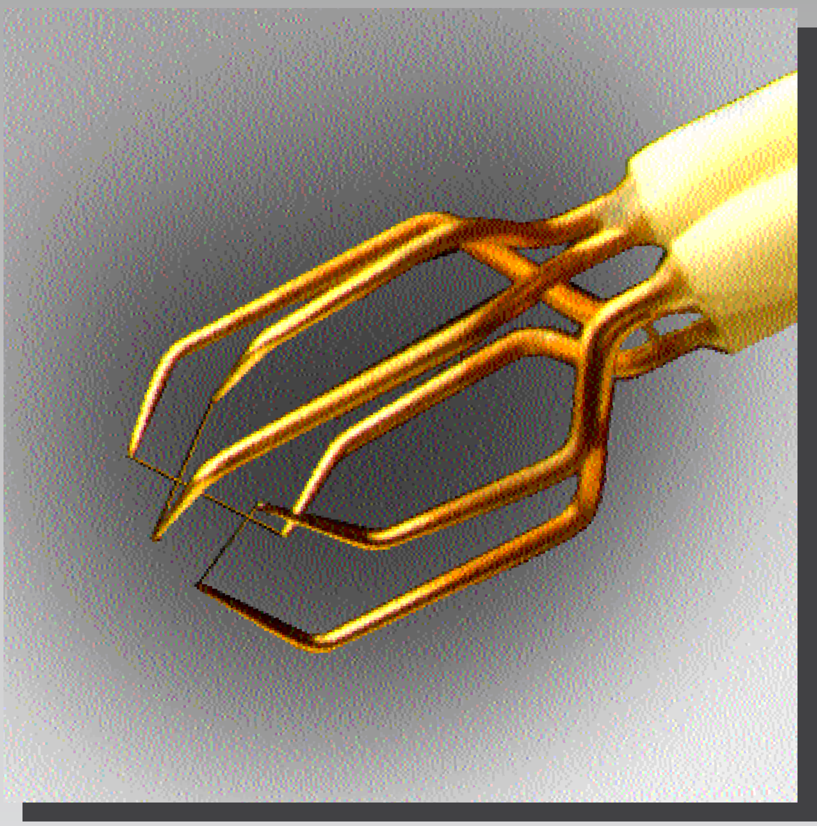
How to measure turbulence with hot-wire anemometers

- a practical guide



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INTRODUCTION

Turbulence is an important process in most fluid flows and contributes significantly to the transport of momentum, heat and mass. Turbulence also plays a role in the generation of fluid friction losses and fluid induced noise. In order to understand the behaviour of fluid flows and in order to design and evaluate vehicles, engines, pumps etc. the study of turbulence is therefore essential. Such studies are carried out by means of suitable instrumentation like hot-wire anemometers (often called CTA or constant temperature anemometers with reference to the operating principle) or laser-Doppler anemometers (LDA) and more recently with particle-imaging velocimetry (PIV). Measurements are often made as supplement to computer modelling (CFD, computational fluid dynamics).

The CTA anemometer works on the basis of convective heat transfer from a heated sensor to the surrounding fluid, the heat transfer being primarily related to the fluid velocity. By using very fine wire sensors placed in the fluid and electronics with servo-loop technique, it is possible to measure velocity fluctuations of fine scales and of high frequencies. The advantages of the CTA over other flow measuring principles are ease-of-use, the output is an analogue voltage, which means that no information is lost, and very high temporal resolution, which makes the CTA ideal for measuring spectra. And finally the CTA is more affordable than LDA or PIV systems.

The booklet is intended to give the reader what he needs to know in order to select and set up a CTA system and to perform measurements of basic turbulent quantities. It goes through all the steps needed in order to carry out reliable measurements starting with a chapter on selection of equipment (anemometer, probes, A/D board etc.) followed by experiment planning, system configuration and installation, anemometer setup, velocity and directional calibration, data acquisition and data reduction. The more knowledgeable reader may only read the text boxes, which are written as comprehensive step-by-step procedures, and skip the text in-between.

Disturbing effects that may influence CTA measurments are mentioned briefly, and finally an example on how to calculate the uncertainty of velocities measured with a CTA anemometer is given. The booklet has a short introduction on the basic theory of the CTA anemometer.

Two appendices give examples on how to setup and acquire data with the Dantec MiniCTA and StreamLine anemometers utilizing the Dantec application software.

1. SELECTING MEASUREMENT EQUIPMENT

1.1 Measuring chain

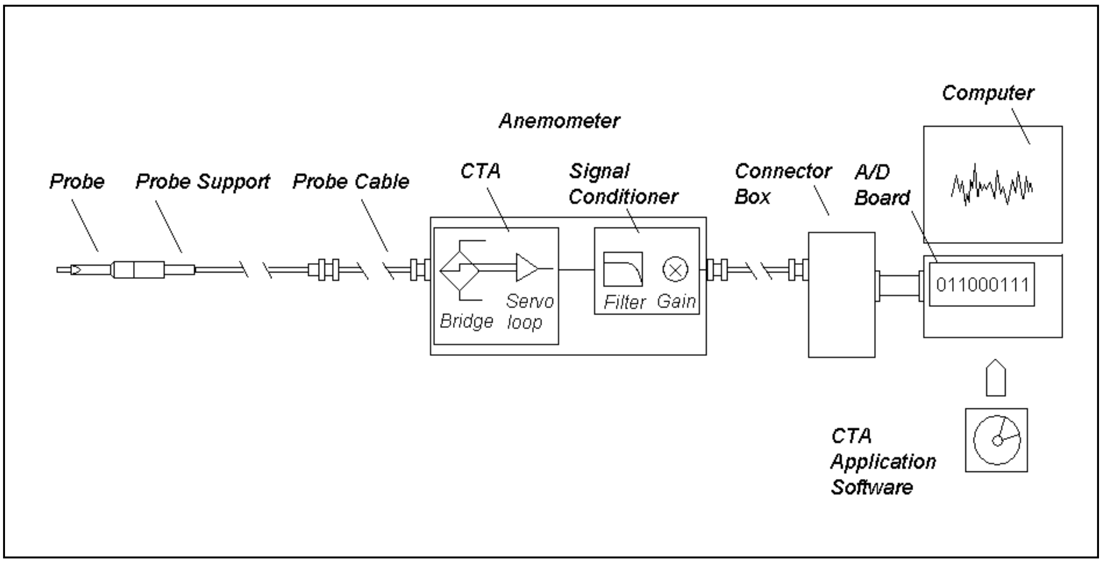


Fig. 1. Typical CTA measuring chain.

The measuring equipment constitutes a measuring chain. It consists typically of a *Probe* with *Probe support* and *Cabling*, a *CTA anemometer*, a *Signal Conditioner*, an *A/D Converter*, and a *Computer*. Very often a dedicated *Application soft-ware* for CTA setup, data acquisition and data analysis is part of the CTA anemometer. A traverse system may be added for probe traverse, when profiles have to be investigated. A dedicated probe calibrator may speed up an experiment and reduce the total costs, as it cuts down expensive wind-tunnel time.

1.2 Probe selection

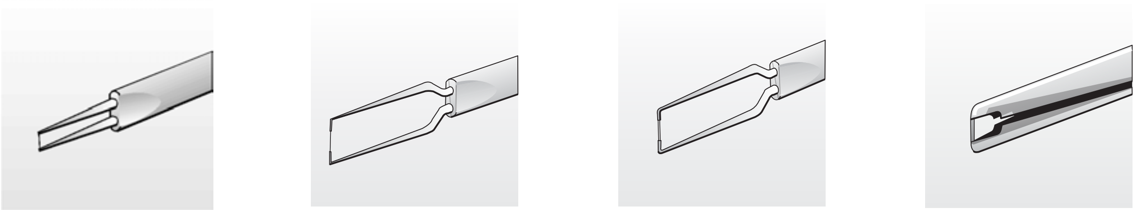
Probes are primarily selected on basis of:

- Fluid medium
- Number of velocity components to be measured (1-, 2- or 3)
- Expected velocity range
- Quantity to be measured (velocity, wall shear strees etc.)
- Required spatial resolution
- Turbulence intensity and fluctuation frequency in the flow
- Temperature variations
- Contamination risk
- Available space around the measuring point (free flow, boundary layer flows, confined flows).

1.2.1 Quick guide to probe selection

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*

1.2.2 Sensor types



Anemometer probes are available with four types of sensors: Miniature wires, Gold-plated wires, Fibre-film or Film-sensors. Wires are normally 5 µm in diameter and 1.2 mm long suspended between two needle-shaped prongs. Gold-plated wires have the same active length but are copper- and gold-plated at the ends to a total length of 3 mm long in order to minimise prong interference. Fibre-sensors are quartz-fibers, normally 70 µm in diameter and with 1.2 mm active length, covered by a nickel thin-film, which again is protected by a quartz coating. Fibre-sensors are mounted on prongs in the same arrays as are wires. Film sensors consist of nickel thin-films deposited on the tip of aerodynamically shaped bodies, wedges or cones.

Sensor type selection:

Wire sensors:

Miniature wires:
First choice for applications in air flows with turbulence intensities up to 5-10%. They have the highest frequency response. They can be repaired and are the most affordable sensor type.

Gold-plated wires:
For applications in air flows with turbulence intensities up to 20-25%. Frequency response is inferior to miniature wires. They can be repaired.

Fibre-film sensors:

Thin-quartz coating:
For applications in air. Frequency response is inferior to wires. They are more rugged than wire sensors and can be used in less clean air. They can be repaired.

Heavy-quartz coating:
For applications in water. They can be repaired.

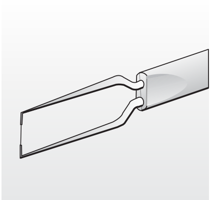
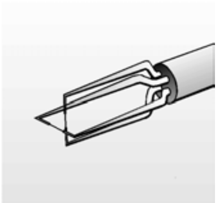
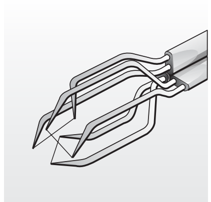
Film-sensors:

Thin-quartz coating:
For applications in air at moderate-to-low fluctuation frequencies. They are the most rugged CTA probe type and can be used in less clean air than fibre-sensors. They normally cannot be repaired.

Heavy-quartz coating:
For applications in water. They are more rugged than fibre-sensors. They cannot normally be repaired.

Note: *Wire probes and fibre-film probes with thin quartz coating can be used in non-conducting liquids.*

1.2.3 Sensor arrays

Probes are available in one-, two- and three-dimensional versions as single-, dual and triple-sensor probes referring to the number of sensors. Since the sensors (wires or fibre-films) respond to both magnitude and direction of the velocity vector, information about both can be obtained, only when two or more sensors are placed under different angles to the flow vector.

Split-fibre and triple-split fibre probes are special designs, where two or three thin-film sensors are placed in parallel on the surface of a quartz cylinder. They may supplement X-probes in two-dimensional flows, when the flow vector exceeds an angle of ±45°. They are not supported by commercially available CTA software.

Sensor array selection:

Single-sensor normal probes:

For one-dimensional, uni-directional flows. They are available with different prong geometry, which allows the probe to be mounted correctly with the sensor perpendicular and prongs parallel with the flow.

Single-sensor slanted probes (45 ° between sensor and probe axis):

For three-dimensional stationary flows where the velocity vector stays within a cone of 90°. Spatial resolution 0.8x0.8x0.8 mm (standard probe). Must be rotated during measurement.

Dual-sensor probes:

X-probes:
For two-dimensional flows, where the velocity vector stays within ±45° with respect to the probe axis.

Split-fibre probes:
For two-dimensional flows, where the velocity vector stays within ±90° with respect to the probe axis. The cross-wise spatial resolution is 0.2 mm, which makes them better than X-probes in shear layers.

Triple-sensor probes:

Tri-axial probes:
For two-dimensional flows, where the velocity vector stays inside a cone of 70° opening angle around the probe axis, corresponding to a turbulence intensity of 15%. The spatial resolution is defined by a sphere of 1.3 mm diameter.

Triple-split film probes:
For fully reversing two-dimensional flows, Acceptance angle is ±180°.

1.3 CTA Anemometer/Signal conditioner

1.3.1 Anemometer selection

Often a CTA anemometer is on hand for an experiment, while it is more seldom that selecting and purchasing an anemometer is part of the experimental planning. In both cases, however, it is important to make sure that the anemometer to be used has the required bandwidth and sufficiently low noise and drift to provide stable and reliable results. In water applications it is also important to check that the CTA bridge can deliver sufficient power to operate the probe at the expected flow velocity.

CTA anemometer and bridge selection:

Research type CTA:

Bandwidth is typically 100-250 kHz, max. 400 kHz.
Noise contributes typically with 0.005% to a background turbulence of 0.1% of 10 kHz bandwith.
Drift typically 0.5 μV per °C.

CTA bridges:

1:20 General purpose bridge for air applications at bandwidths below approx. 250 kHz.
1:20 General purpose bridge with high power for water applications.
1:1 Symmetrical bridge for bandwidths up to 400 kHz, or for long probe cables up to 100 m (reduces max. bandwidths to typically 50 kHz).

Setup:

Automatic setup of and operation of CTA bridge via application software.

Dedicated type CTA:

Bandwidth is typically 10 kHz.
Noise on output signal is typically 1-2 mV.
Drift typically 0.5 μV per °C.

CTA bridges:

1:20 General purpose bridge for air applications at a bandwidth up to approx. 10 kHz.

Setup:

Manual setup and operation of CTA bridge.

Research type anemometers are normally multi-channel systems with up to 6 or more CTA channels. They have built-in Signal conditioners for amplification and filtering of the CTA signal before A/D conversion.

Dedicated anemometers are single-channel instruments supporting only one sensor. They do normally only have a low-pass filter for the output signal. They can be combined for multi-point measurements.

1.3.2 Signal conditioner

Most CTA anemometers have built-in *Signal Conditioners* for *high-pass* and *low-pass filtering* and for *amplification* of the CTA signal.

Signal conditioner selection:

Offset:
Should ideally cover the input range of the A/D board. In practice, however, it suffices to cover the expected range of the CTA output signal, e.g. 0-5 Volts.

Gain:
Improves A/D board resolution. A gain of 16 gives a 12-bit A/D board the same resolution as a 16-bit board.

High-pass filter:
Removes the DC-part of the signal. Is only needed, when low frequency fluctuations have to be removed from the signal prior to spectral analysis.

Low pass filter:
Removes electronic noise from the signal and prevents folding back of spectra (aliasing). The filter should be as steep as possible. Research anemometers normally have a –60dB/decade roll-off, while dedicated simpler anemometers may have –20 dB/decade.

1.4 A/D board

The CTA signal is acquired via an A/D converter board and saved as data-series in a computer.

Selecting the A/D board:

Number of channels:
Shall as a minimum equal the number of CTA channels plus additional channels (e.g. temperature) needed in the experiment.

Input range:
Shall cover as a minimum the CTA voltage range. A 0-10 Volts range is well suited for most anemometers and applications.

Input resolution:
Shall be sufficient to provide the required resolution in converted data. A 12-bit board typically gives a velocity resolution of 0.1 to 0.2%.

Sampling rate SR:
Shall be minimum two times the maximum frequency in the flow: $SR=2\cdot f_{max}$
SR is reduced by the number of channels, n, in use: $SR(n)=1/n\cdot 2\cdot f_{max}$
A 100 kHz board covers most low-to-medium velocity applications (<100 m/s).

Simultaneous sampling:
May be needed when correlation between fast sampled multiple channels (e.g. Reynolds shear stress) is required.
Check the sampling rate per channel, as it may be significantly reduced due to delays on the board as compared with the sampling rate for consecutively sampled signals with the same board.

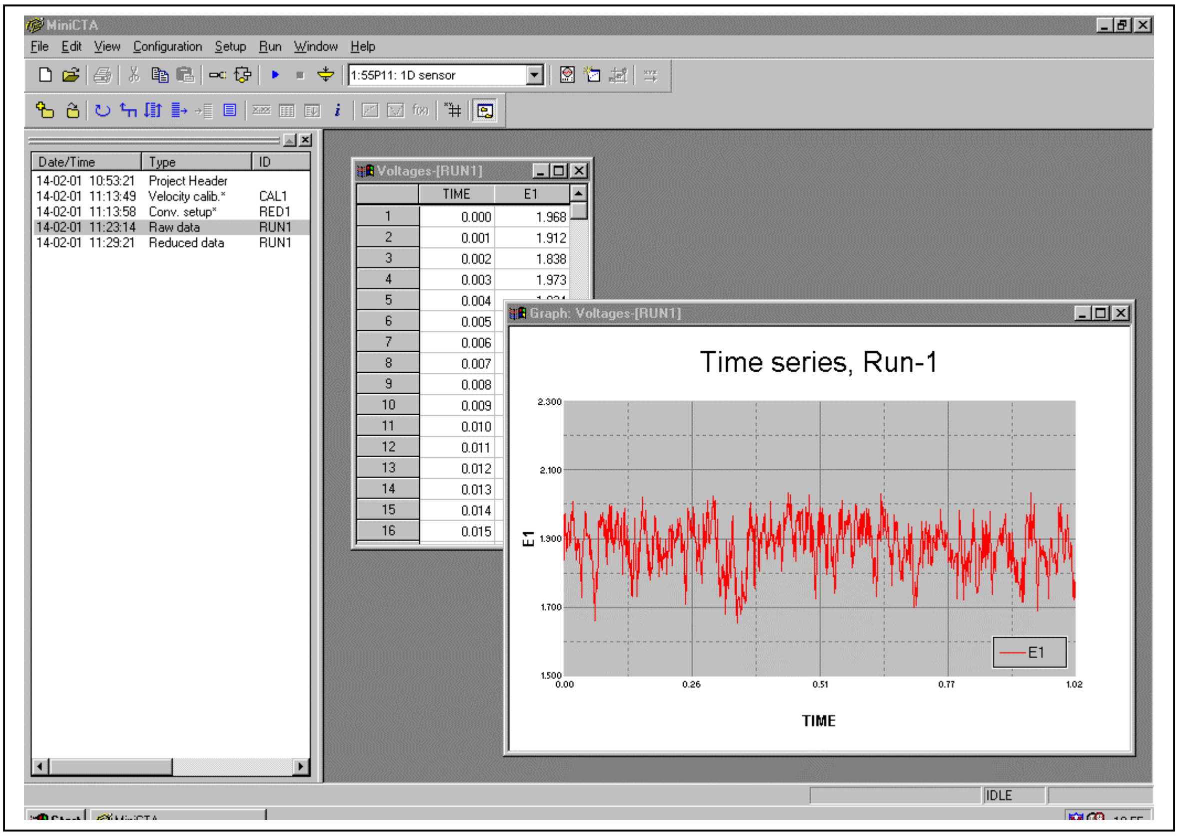
External triggering:
Needed to start the data acquisition by an event related to the flow.

1.5 Computer

The choice of computer to be used for CTA measurements is normally not critical. Speed and memory storage are normally more than sufficient for most applications. It is, however, important to ensure that the CTA controller, the A/D board driver and the traverse driver are compatible, i.e. runs under the same operative system and can be called from the same application software. Also that the required number of com ports for communication with the CTA anemometer and the traverse system is available.

1.6 CTA application software

Commercially available CTA anemometers are normally delivered together with an application software. Advanced software packages control the anemometer and carry out automatic setup of both CTA bridge and signal conditioner [14]. They also perform automatic velocity and directional calibrations and they can be programmed to perform automatic experiments with probe traversing and data equisition. Finally data are converted into engineering units and reduced to relevant statistical quantities: moments, spectra etc. Application software for manually operated anemometers is also available. Except for the anemometer and calibrator drivers, they have by and large the same functionality as the advanced packages.



Note: It is highly recommended to use professional CTA application software when at all possible in order to reduce the time and costs it otherwise takes to start up. In special cases, where the CTA is part of a large measurement system with input from many other types of instruments including the control of windtunnels and traverses, it may be worthwhile considering writing ones own software. Even then, it may be sensible to use the velocity and directional calibration routines offered by a professional application software.

1.7 Traverse system

A traverse system is needed, if probe movement is part of the experimental procedure. It may have up to three axis and a rotation unit, if used for slanting probes.

Traverse selection:
Axis:
Number and range of traverse axis shall fit to the experiment.
Resolution:
Linear resolution shall be sufficient. Commercially available traverses for CTA probes normally have a resolution better than 0.01 mm and can be repositioned within approx. ±0.1 mm.
Control:
Automatic traverse is most conveniently controlled from the CTA application software.
Impact on flow pattern:
The traverse should not disturb the flow at the probe position. This may be achieved by using aerodynamically shaped probe mounts on the traverse.

The traverse should be rigid so that the parts exposed to the wind load do not vibrate or bend. Such vibrations or bending will bias the velocity measurement.

1.8 Calibration system

A calibration system is normally not considered part of the measuring chain. It plays, however, an important role for the accuracy and the speed, with which an experiment can be carried out. Calibrations may be performed in a dedicated calibrator with a low-turbulent free jet, whose velocity is calculated on basis of the pressure drop over its exit. Calibrations can also be performed in the wind-tunnel, where the experiments are going to take place, with a pitot-static tube as the velocity reference.

Calibration facility:
Dedicated probe calibrator:
Velocity range. From a few cm/s to several 100 m/s.
Accuracy: Typically ±0.5% of reading above 5m /s.
Additional features: May be used for directional calibration of multi-sensor probes.

Wind-tunnel with Pitot-static tube:
Velocity range: From approx. 2 m/s to typically 50 m/s
Accuracy: Typically ±1% of reading above 5 m/s. Depends on pressure device and decreases at low velocities.

2. PLANNING AN EXPERIMENT

The quality of fluid dynamic measurements and the efficiency of the experimental procedure very much depends on the selection of the equipment, inclusive the application software, and on the planning of the experiment. Qualified decisions depend on the capability to identify the measurable quantities and to select the data analyses needed to provide the required results.

What to do:	***Check list:***
Know what you want to measure, the physical variable, the statistical functions, the ultimate presentation. *Know* your sensor: sensitivity limitations, potential problems. *Know* the results beforehand. If you do not guess, cross check, explore. *Design* the measurement. *Estimat*e optimum data rate, measurement time, number of samples needed. *Check* the function of equipment by varying parameters. Is the system immune to small changes in bandwidth, range, gain …. *Monitor* the results online – things may change: temperature, conditions during a traverse. Do not leave and go for coffee!	*Define* quantities to be measured: - Higher order moments (mean, standard deviation, turbulence, shear stress, etc.). - Frequency distribution (spectra) - Eddy sizes (length scales) *Define* distribution of measuring points: - Single point measurement - Profiles (probe traverse) - Simultaneously in many points *Select* Equipment and software on basis of: - Flow medium: Gas or liquid. - Dimensions: 1-, 2- or 3-dimensional. - Fluctuations: Turbulence intensity, length scales, frequency distribution. - Temperature: Constant or varying. - Quantity to be measured: Velocity components, shear stress, temperature etc. *Define* Experiment procedure on basis of: - Type of flow field: Free or internal flows, wake flow, boundary layer flow, reversing flow. - Point distribution: Single-point or distributed. - Data analysis: Amplitude-, time- or spectral domain *Define* Data analysis on the basis of: - Required result versus measured quantity. - Equipment setup and data conversion setup.

Note: *Some of the characteristics, e.g. length scales and frequency distribution, may be unknown prior to an experiment and have to be measured before the final setup of the experiment.*

3. EXPERIMENT STEP BY STEP PROCEDURE

When the flow and parameters of interest are defined and the necessary hardware is installed and configured (*Chapter 1* and *2*), the experimental procedure consists of the following steps (numbers in bracket refer to relevant chapters):

HARDWARE SETUP:

1. Adjust overheat ratio ***(5.1.1)***.
2. Measure ambient reference temperature, if temperature variations are expected.
3. If need be, check system response with square wave test (***5.1.2)***.
4. Set low-pass filter in Signal Conditioner (***5.2.1)***.

VELOCITY CALIBRATION:

5. Expose the probe to a set of known velocities and determine the transfer function (***6)***.

DIRECTIONAL CALIBRATION:

6. Only for 2- and 3-D probes, and only if high accuracy is required. Otherwise use manufacturer's defaults for yaw and pitch coeffcients (*7)*.

CONVERSION AND DATA REDUCTION:

7. Transfer function provides calibration velocities ***(8.1.1-8.1.2-8.1.3)***.
8. Decomposition using yaw and pitch coefficients provides velocity components ***(8.1.4 - 8.1.5)***.
9. Data analysis module provides reduced data. (***10)***.

DEFINE EXPERIMENT:

10. Select hardware setup

    Option 1: Adjust overheat ratio if temperature changes are expected ***(11.2)***.

    Option 2: Leave overheat resistor constant (requires temperature correction of data, if temperature changes ***(11.2)***.
11. Probe movement: Define traverse grid (for measurements in many points)

DEFINE DATA ACQUISITION:

12. Sampling frequency and number of samples ***(9)***.

TEST RUN:

13. Place the probe in the flow and acquire data. Check that reduced data (mean velocity, standard deviation etc.) are as expected.

RUN EXPERIMENT:

14. Move the probe to position, readjust hardware, if need be, and acquire probe voltages ***(11)***.

CONVERT AND REDUCE DATA:

15. Load the data and apply the selected conversion/reduction routine ***(10)***.

PRESENTATION OF DATA:

16. Present data in graphs or export them to a report generator.

4. SYSTEM CONFIGURATION

System configuration is the process of mounting and interconnecting the selected probes, cables, CTA anemometers, signal conditioners and A/D channels. The configuration may also include a Traverse system for the probe.

4.1 Probe mounting and cabling

4.1.1 Probe mounting and orientation

The probe is mounted in the flow with the same orientation as it had during calibration. Preferably with the wire perpendicular to the flow and the prongs parallel with the flow.

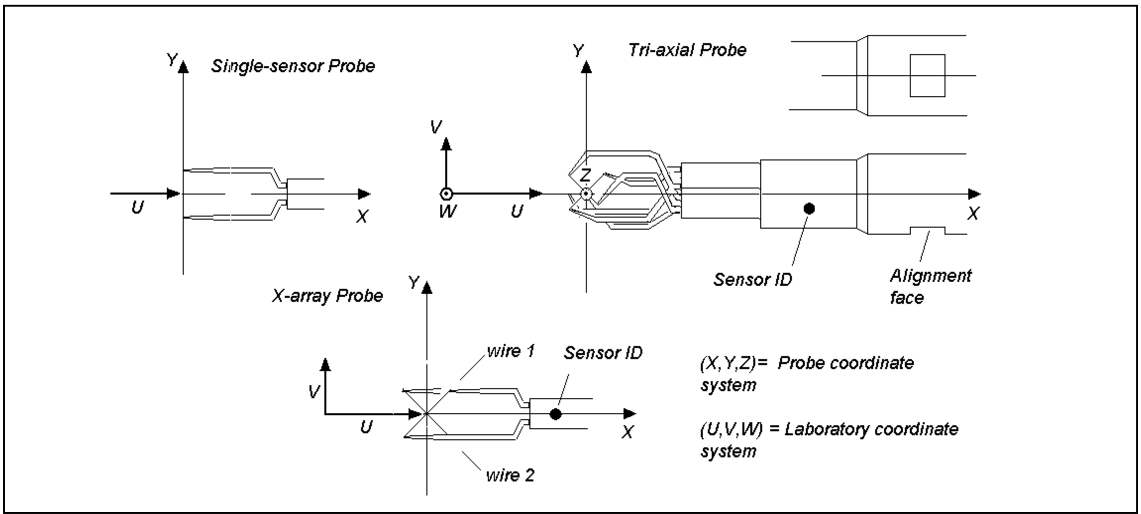


Fig. 2. Probe orientation with respect to laboratory coordinate system.

Straight probes are mounted with the probe axis parallel with the dominant velocity direction. It is recommended that the probe coordinate system (*X,Y,Z*) coincides with the laboratory coordinate system (*U,V,W*).

The probe is mounted in a probe support, which is equipped with a cable and BNC connector, one for each sensor on the probe. Film probes are equipped with fixed cables and need no supports. Probe bodies and the probe support are designed so that their outer surfaces are electrically insulated from the electrical circuitry of the probe or anemometer circuit. They can therefore be mounted directly to any metal part of the test rig without the risk of ground loops.

It is important to note that the BNC connectors ***do not*** *make electrical contact with any metal parts of the rig or elsewhere. The BNC connectors represent the signal ground and may therefore carry ground loops. It is also important that the BNC connectors on dual- or triple-sensor supports do not touch each other, as it will influence the floating amplifiers in the CTA.*

It is therefore recommended to cover all BNC connectors with a length of plastic tube.

Important: The probe should only be mounted in its support or removed from it, when the CTA is switched to Stand- by or the power to the CTA is disconnected.

4.1.2 Cabling

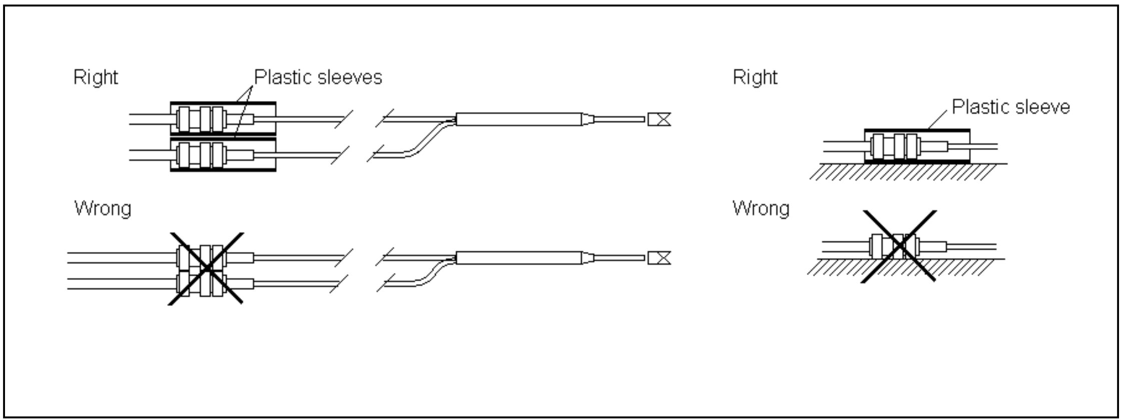


Fig. 3. Avoiding ground loops and noise pickup.

The distance between the probe and the CTA should be kept as small as possible. The standard cable length is 4 meters probe cable plus 1 meter support cable, and this combination should be used if at all possible in order to obtain maximum bandwidth and in order to avoid picking up more noise than need be. If longer cables are necessary, it is important to follow the lengths recommended by the manufacturer for the actual CTA bridge (normally 20 or 100 m).

It is recommended to use the BNC-BNC cables delivered together with the CTA by the manufacturer in order to match the cable-compensating network in the bridge.
If this is not done, the bridge may become unstable and deliver a useless oscillating voltage output or, in the worst case, burn the sensor.

4.1.3 Liquid grounding

Film probes mounted in liquids may be damaged, if a voltage difference between the sensor film and the liquid builds up by electric charges in the flowing medium. If such charge build up occurs, the insulating quartz coating may break down and the thin-film will be etched away due to electrolysis. The liquid must therefore be grounded to the anemometer's signal ground as close to the probe as possible.

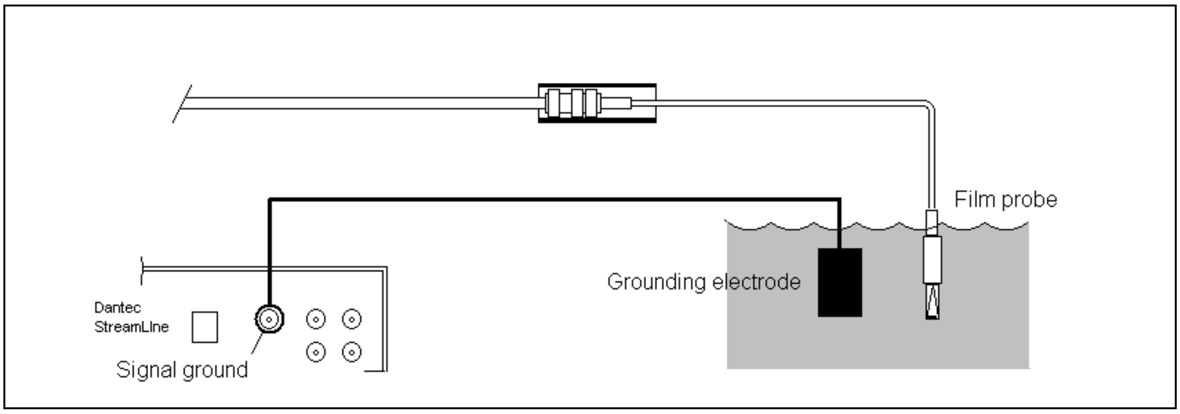


Fig. 4. Grounding of liquid to Signal ground near film probe.

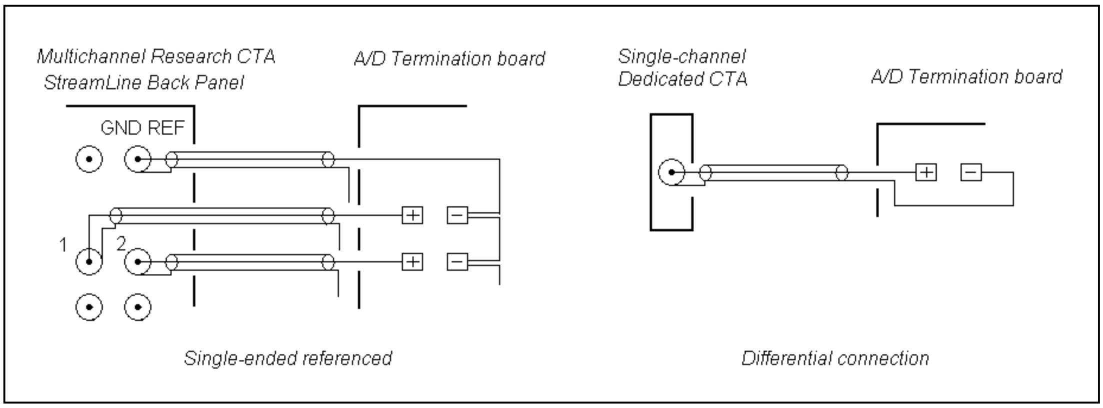
4.2 CTA configuration

4.2.1 CTA bridge

The CTA bridge configuration is selected on the basis of the required *bandwidth*, the required *power* to the probe (related to fluid medium, velocity and probe type) and on basis of the *distance* between probe and the CTA.

Standard CTA bridge: Bridge ratio *1:20* Resistor in series with the probe: normally 20 ohms. This bridge configuration can be used in the most applications. *Symmetrical CTA bridge (research type anemometers):* Bridge ratio *1:1* Resistor in series with the probe: normally 20 ohms. This bridge is recommended for *very low turbulence intensities* (typically less than 0.1%) or *very high fluctuation frequencies* (typically above 200-300 kHz). Or when *long cables* between probe and CTA are needed. It has lower noise and can be balanced to a higher bandwidth than the 1:20 bridge. *High power CTA bridge (research type anemometers):* Bridge ratio *1:20* Resistor in series with the probe: 10 ohms. Recommended for *high power* applications (water at high speeds, e.g. 1 m/s or above). Probe current is almost doubled (typically 0.8 amps. compared with 0.4-0.5 amps.)

4.2.2 Connecting CTA output to A/D board input channels.



It is important to follow the manufacturer's instructions when connecting the CTA output to the A/D board input. Research anemometers where the CTA modules have separate power supplies and common signal ground may be connected single-ended referenced (i.e. with common ground). Dedicated anemometers in separate housings should normally be connected differentially in order to avoid cross-talk between channels. The cable length between the CTA output and the A/D board input should be kept as short as possible, preferably a few meters. The configuration of the A/D board is done in the manufacturer's application software.

4.3 Traverse System

The Traverse system is used to move the probe around in the flow. It is selected on the basis of the *number of axis* to be traversed, the *size of the area* to be traversed, the *positioning accuracy* and the expected *forces from the flow* acting on the traverse.

When a PC controlled traverse system is selected, it is important to make sure that the moving of the traverse and the acquisition of data can be timed securely. The most practical solution is when the traverse can be moved from the CTA application software, i.e. the traverse is part of the hardware configuration, or when the CTA data can be acquired in the same software, which controls the traverse. The communication with the traverse is often done via a serial comport or via a GPIB interface.

5. ANEMOMETER SETUP

The anemometer setup consists of *CTA hardware setup* and *Signal conditioner offset and gain adjustment.*

5.1 CTA hardware setup

The hardware setup consists of an *overheat adjustment* (static bridge balancing) and a *square wave test* (dynamic balancing). When a signal conditioner is part of the CTA, the hardware setup also includes *low-pass filter* and optional *gain* settings.

5.1.1 Overheat adjustment

The overheat adjustment determines the working temperature of the sensor. The overheat resistor (decade resistor) in the right bridge arm is adjusted, so that the wanted sensor operating temperature is established when the bridge is set into *Operate*. The cold and warm resistors are related via the overheating ratio, a:

$$a = \frac{R_w - R_0}{R_0}$$ where R_w is the sensor resistance at operating temperature T_w and R_0 is its resistance at ambient (reference) temperature T_0.

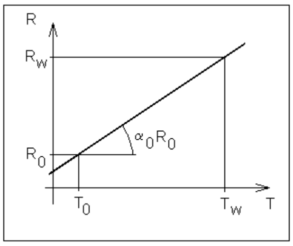
The over temperature T_w-T_0 can be calculated as:

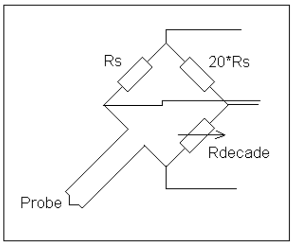
$$Tw - To = \frac{a}{\alpha_0}$$ where α_0 is the sensor temperature coefficient of resistance at T_0.

The probe leads resistance and the resistances of the support and cable are normally provided by the manufacturer and need therefore not to be measured separately, unless high accuracy in setting the over temperature is required.

Some dedicated CTA anemometers do not have facilities for measuring the probe cold resistance. In such cases it may suffice to use the resistance values stated on the probe container.

Overheat adjustment procedure:





Measure the total resistance $R_{tot,0}$ at ambient temperature T_0 and calculate the active sensor resistance:

$$R_0 = R_{tot,0} - \left(R_{leads} + R_{\sup port} + R_{cable}\right)$$

R_{leads} = probe leads resistance, $R_{support}$ = support resistance and R_{cable} = cable resistance.

Select a suitable overheat ratio, *a*.

Recommended values are *a*= 0.8 in air (over temperature approx 220 °C)

and *a*=0.1 in water (over temperature approx. 30 °C).

Calculate the decade resistance as:

$$R_{dec} = BR \cdot \left[(1 + a) \cdot R_0 + R_{leads} + R_{\sup port} + R_{cable}\right]$$

BR= bridge ratio=20 (in most CTA's)

Adjust the decade resistance to $R_{dec.}$

Note: *If the probe resistance is measured with an ordinary ohm meter, it is recommended to check the measuring current. The current should not exceed 1 mA when measuring the resistance of a 5 µm wire probes in order to avoid heating the wire.*

5.1.2 How to use overheat adjustment

The practical use of overheat adjustment depends on how the temperature varies during setup, calibration and experiment.

The temperature is ***constant*** throughout (T varies less than for example ±0.5 °C):

The overheat is adjusted *once* at the start of the experiment and left untouched during calibration and data acquisition ("*Automatic overheat adjust*" is *disabled* in computer controlled anemometers).

The temperature ***varies*** from setup to calibration and during the experiment. There are two options:

1. Overheat adjust. The probe resistance is measured, and the overheat is *readjusted* before calibration and before to each data acquistion. The overheat ratio will then be the same in all situations and the tempearture influence minimised. ("*Automatic overheat adjust*" is *enabled* in computer controlled anemometers).

2. *Temperature correction:* The overheat is adjusted *once* and left untouched during calibration and data acquisition. The temperature is measured during calibration and during the experiment and used to correct the anemometer voltages before conversion and reduction.

See ***Chapter 11.2.***

5.1.3 Square wave test

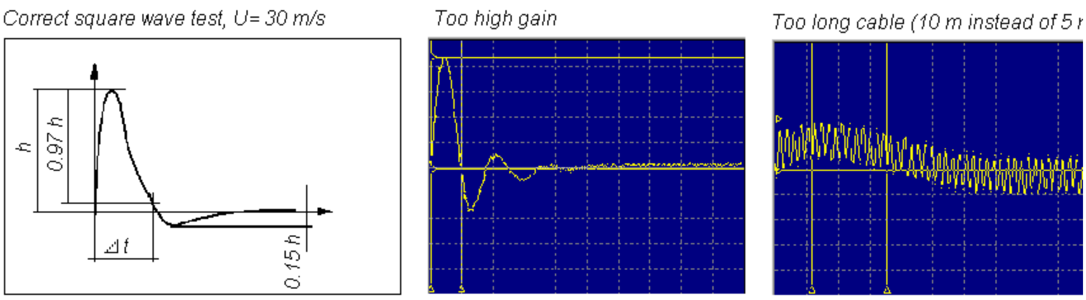
The square wave test, or dynamic bridge balancing, serves two purposes: It can be used to optimise the bandwidth of the combined sensor/anemometer circuit or simply to check that the servo-loop operates stable and with sufficiently high bandwidth in the specific application. It is carried out by applying a square wave signal to the bridge top. The time it takes for the bridge to get into balance is related to the time constant, and hence the bandwidth, of the system. Most CTA anemometers have built-in square-wave generators. If not, they normally have input for an external square wave generator.

Square wave test procedure:

Expose the probe to the expected maximum velocity.

Connect an oscilloscope to the CTA output, *if* the square wave is not displayed in the application software.

Apply the square wave to the bridge.



Adjust amplifier filter and gain until the response curve gets a 15% undershoot. The response should be smooth without "ringing" either at the top or at the zero line.

Determine Δt being the time it takes the servo-loop to regulate back to 3% of its maximum value with an undershoot of 15%.

Calculate the bandwidth of the probe/anemometer system (or cut-off frequency) f_c:

$$f_c = \frac{1}{1.3 \cdot \Delta t}$$ (wire probes) [10] $$f_c = \frac{1}{\Delta t}$$ (fibre-film probes) [11]

The bandwidth is defined as the frequency, at which the fluctuation amplitude is damped by a factor 2 (–3 dB limit).

Note: *For wire probes up to 100 m/s the amplitude damping starts at frequencies 0.3 - 0.5 times smaller than the –3 dB cut-off frequency determined by the square wave test.*

The response can be optimised by adjusting the amplifier filter and gain. High gain setting gives high bandwidth, but also greater risk for the servo-loop to become unstable. It is therefore often recommended to reduce the gain in order to run safely.

Most CTA manufacturer's are recommending default settings for gain and filter, which can be used in most applications. Dedicated CTA anemometers often have fixed setup for the servo-loop, which works within the bandwidth stated for them without further adjustment by the user.

5.2 Signal Conditioner setup

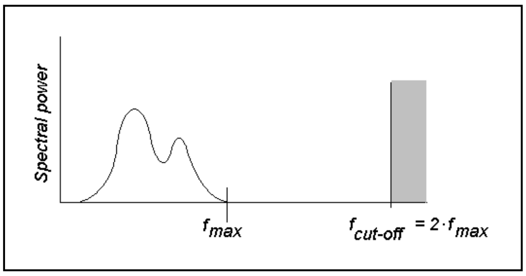
The signal conditioner provides facilities for the filtering and the amplification of the CTA signal prior to digitizing by the A/D converter.

5.2.1 Low-pass filtering.

Low-pass filtering is used in order to remove noise and to prevent higher frequencies from folding back (anti-aliasing). The setting of the low-pass filter relates to the highest frequency in the flow.

Low-pass filtering:

Estimate the highest frequency: f_{max}.
Select the cut-off, frequency: $f_{cut-off} = 2 \cdot f_{\max}$
Select the filter setting closest to the cut-off frequency.



If low-pass filtering is not performed, the energy at frequencies lower than $f_{cut-off}$ will be contaminated by higher frequencies if the Nyquist sampling criteria is applied. This appears as a false energy peak in the power spectrum.

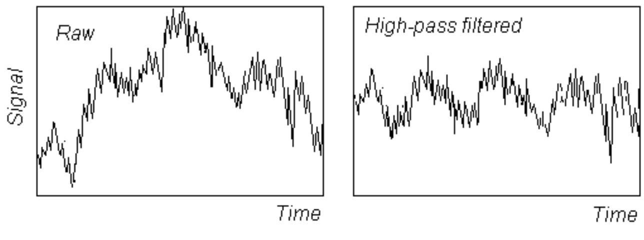
5.2.2 High-pass filtering

High-pass filtering is used to clean the signal, if FFT spectra calculation is required. When the CTA signal fluctuates on a timescale longer than the total length of the data record, it will give unwanted high frequency contributions in an FFT-based spectrum. Otherwise it should *not* be applied.

High-pass filtering:

Select the data record length, t_{record}.

Calculate the high-pass cut-off frequency: $f_{cut-off} = \dfrac{5}{2 \cdot t_{record}}$



This eliminates waves with a wavelength larger than 2/5 of the record length. Shorter waves will not be interpreted as erroneous non-stationary contributions to the signal.

High-pass filtering will make the signal stationary. It should be noted that no spectral information is available below the cut-off frequency of a high-pass filter.

High-pass filters with a sharp and low cut-off frequency are difficult to establish and they very often have large phase lags. They should therefore be used with care. A better solution might be to perform digital filtering of the full data set with, for example, a sixth order filter.

5.2.3 Applying DC-offset and Gain

DC-offset:

The CTA signal level may be reduced by subtraction of a DC-offset voltage. This is necessary if the signal moves outside of the range of the A/D board, when a high amplification of the signal is needed prior to digitizing.

DC-offset procedure:
Determine the minimum value E_{min} of the CTA signal to be measured.
Adjust the DC-offset in the Signal conditioner to: $E_{offset} = E_{min}$

Note: *Avoid applæying DC-offset if possible, as the signal then no longer directly represents the power transferred from the sensor to the fluid. The usual temperature correction routines are therefore no longer valid, unless the signal is reconstructed by adding the DC-offset prior to correction.*

Signal amplification (Gain)

The CTA signal may have to be amplified in order to utilise an A/D board with a resolution, that is too small for the application.

In most low to medium velocity applications with a turbulence intensity above 2% to 3 %, a 12 bit A/D board is sufficient without the need for amplification of the CTA signal. A 12 bit A/D board has a resolution of 2.4 mVolts in the 0-10 Volts range. By applying a gain of 16 to the CTA signal prior to digitization the 12-bit resolution is improved to 0.15 mV corresponding to that of a 16 bit board with CTA gain 1. This is sufficient for measurement of background turbulence down to approximately 0.1%.

Gain setting procedure:
Determine the required velocity resolution ΔU in m/s.
Calculate the mean slope $\delta E/\delta U$ of the probe calibration curve in the velocity range of interest:

$$\frac{dE}{dU} = \frac{E(U_2) - E(U_1)}{U_2 - U_1}$$ where *E(U)* is the CTA voltage at the velocity *U*.

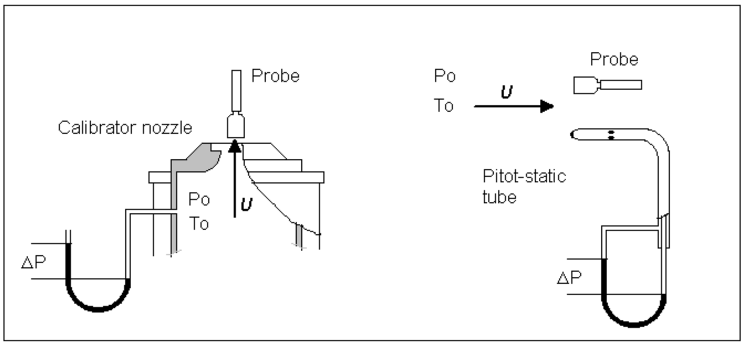
Calculate the required voltage resolution: $\Delta E = \Delta U \cdot \frac{dE}{dU}$

Calculate the gain *G* as: $G = \frac{\Delta E_{AD}}{\Delta E}$ where ΔE_{AD} is the resolution of the A/D board.

6. VELOCITY CALIBRATION, CURVE FITTING

Calibration establishes a relation between the CTA output and the flow velocity. It is performed by exposing the probe to a set of known velocities, U, and then record the voltages, E. A curve fit through the points (E,U) represents the transfer function to be used when converting data records from voltages into velocities. Calibration may either be carried out in a dedicated probe calibrator, which normally is a free jet, or in a wind-tunnel with for example a pitot-static tube as the velocity reference. It is important to keep track of the temperature during calibration. If it varies from calibration to measurement, it may be necessary to correct the CTA data records for temperature variations.

Velocity calibration procedure:



Mount the probe in the calibration rig with the same wire-prong orientation as will be used during the experiment.

- Single-sensor probes: with the prongs parallel with the flow.

- X-probes and Tri-axial probes: with the probe axis parallel with the flow.

Record the ambient conditions: Temperature, T_a , and barometric pressure, P_b.

Setting to operate:

1) Calibration with *temperature correction*:

   Switch the anemometer to Operate with the previously established overheat setup.

2) Calibration with *overheat adjustment*:

   Balance the bridge immediately before calibration and establish a new overheat setup using the same overheat ratio a.

Choose min. and max. calibration velocity, $U_{min,cal}$ and $U_{max,cal}$,

Choose number of calibration points (a minimum of 10 points is recommended).

Choose velocity distribution (logarithmic distribution is recommended).

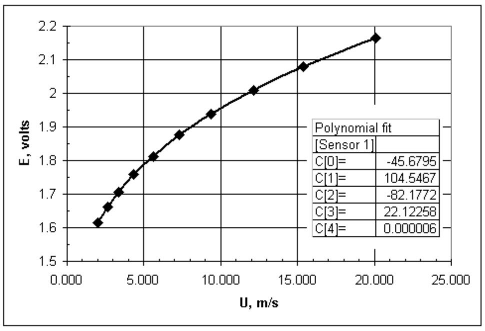
Create the velocities and acquire the CTA voltage together with velocity and ambient temperature in all points.

Research type anemometers may be delivered with automatic calibrators and calibration routines in their application software, thus offering fully automatic calibrations inclusive of curve fitting.

CTA application software packages contain curve fitting procedures, which correct the voltages and calculates the transfer functions on basis of advanced curve fitting methods eliminating the need for any data manipulations by the user.

Curve fitting of calibration data (manual procedure):

U	E	T	Pbar	Ecorr
m/s	volts	C	Pa	volts
2.019	1.614	26.0	100.652	1.615
2.622	1.661	26.0	100.654	1.662
3.358	1.705	26.0	100.66	1.706
4.360	1.758	25.9	100.663	1.759
5.621	1.813	25.9	100.66	1.814
7.324	1.876	25.9	100.654	1.877
9.379	1.939	25.9	100.652	1.94
12.121	2.01	25.9	100.652	2.011
15.364	2.08	25.9	100.657	2.081
20.101	2.166	25.9	100.657	2.167



Arrange the probe data in a table, for example in Excel, containing velocity U, CTA voltage E, fluid temperature T_a and pressure P_b.

Correct the voltages E for temperature variations during calibration, see Chapter 7.1.2.

Polynomial curve fitting:

Plot U as function of E_{corr}

Create a polynomial trend line in 4th order:

$U = C_0 + C_1 E_{corr} + C_2 E_{coor}{}^2 + C_3 E_{corr}{}^3 + C_4 E_{corr}{}^4$, *Co* to C_4 are calibration constants.

The polynomial curve fit is normally recommended, as it makes very good fits with linearisation errors often less than 1%.

Note: Polynomial curve fits may oscillate, if the velocity is outside the calibration velocity range.

Power law curve fitting:

Plot E^2 as function of U^n in double logarithmic scale (n=0.45 is a good starting value for wire probes).

Create a linear trend line. This will give the calibration constants A and B in the function:

$E^2 = A + B \cdot U^n$ (King's law [15])

Vary n and repeat the trend line until the curve fit errors are acceptable.

Power law curve fits are less accurate than polynomial fits, especially over wide velocity ranges, as n is slightly velocity dependent.

Velocity calibration of X-probes and Tri-axial probes:

The calibration velocity range must be expanded with respect to the velocity limits expected during the experiment thus making sure that the curve fit is valid over the full angular acceptance range of the probes. $U_{min,exp}$ *and* $U_{max,exp}$ *are peak values.*

	$U_{min,cal}$	$U_{max,cal}$
X-probes	$0.1 \cdot U_{min,exp}$	$1.5 \cdot U_{max,exp}$
Tri-axial probes	$0.15 \cdot U_{min,exp}$	$1.6 \cdot U_{max,exp}$

7. DIRECTIONAL CALIBRATION

Directional calibration of multi-sensor probes provides the individual directional sensitivity coefficients (yaw factor k and pitch-factor h) for the sensors, which are used to decompose calibration velocities into velocity components.

Note: *In many situations, where optimal accuracy is not needed, the manufacturer's default values for k and h can be used, eliminating the need for individual directional calibration.*

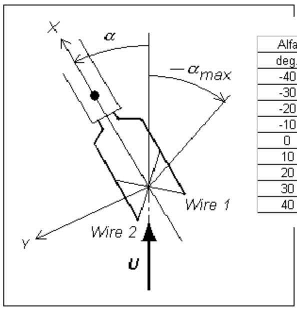
7.1.1 X-array probes

The yaw coefficients, k_1 and k_2, are used in order to decompose the calibration velocities U_{cal1} and U_{cal2} from an X-probe into the U and V components.

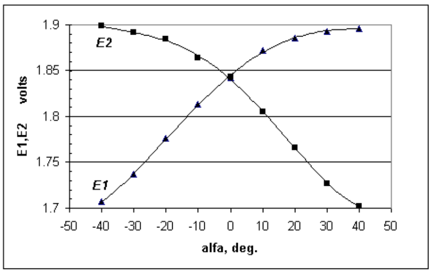
Directional calibration of X-probes requires a rotation unit, where the probe can be rotated on an axis through the crossing point of the wires perpendicular to the wire plane. Calculation of the yaw coefficients requires that a probe coordinate system is defined with respect to the wires (see the sketch below), and that the probe has been calibrated against velocity.

X-probe calibration procedure:

Define probe coordinate system *(X,Y)* with respect to wire 1 and 2 as shown below:



Alfa	E1	E2
deg.	volts	volts
-40	1.707	1.899
-30	1.737	1.892
-20	1.777	1.884
-10	1.813	1.864
0	1.842	1.843
10	1.872	1.805
20	1.886	1.766
30	1.893	1.727
40	1.896	1.703



Mount the probe in the rotating holder oriented as shown above.

Estimate the maximum angle α_{max} , which is expected in the experiment between the velocity vector U_α and the probe axis. In most cases α_{max} is selected to =40°.

Select the number of angular positions for the calibration.

Expose the probe to the middle calibration velocity $U_{dir,cal} = 1/2 \cdot (U_{min,cal} + U_{max,cal})$

Rotate the probe to the $-\alpha_{max}$ position and acquire the voltages E_1 and E_2 from the two sensors.

Check that E1 is bigger than E_2 and that E_1 increases, while E_2 decreases, when the probe is moved to next angular position. If not turn the probe180° around its X-axis and start again.

Read E_1 and E_2 in each angular position.

Calculate the squared yaw factor k_1^2 and k_2^2 for sensor *1* and sensor *2* in each position using the equations in *Chapter **8.1.4***.

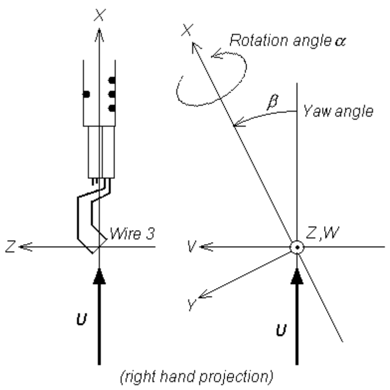
Calculate the average of the k_1^2 and k_2^2 ,respectively, factors and use them as sensitivity factors for the two sensors.

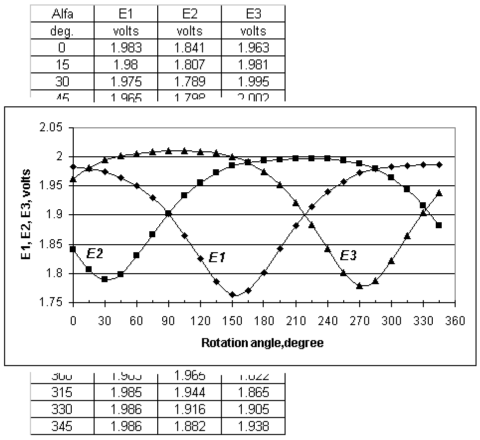
7.1.2 Tri-axial probes

The directional sensitivity of tri-axial probes is characterised by both a yaw and a pitch coefficient, *k* and *h*, for each sensor. Calibration of tri-axial probes requires a holder, where the probe axis (X-direction) can be tilted with respect to the flow and thereafter rotated 360° around its axis. Proper evaluation of the coefficient requires that a probe coordinate system is defined with respect to the sensor-orientation. Directional calibration is made on the basis of a velocity calibration.

Tri-axial probe calibration procedure:

Define a probe coordinate system (normally use the manufacturer's suggestion):





Mount the probe in the rotating holder with the probe axis in the flow direction and wire no. 3 in the XZ plane of the calibration unit system, corresponding to α=0.

Estimate the maximum angle β_{max} , which is expected in the experiment between the velocity vector and the probe axis. In most cases β_{max} is selected to 30°.

Select the number of angular positions α for the calibration, normally 24 corresponding to 15° steps.

Expose the probe to the mid calibration velocity range $U_{dir,cal} = 1/2 \cdot (U_{min,cal}+U_{max,cal})$ and acquire the voltages E_1 , E_2 and E_3 from the three sensors.

Tilt the probe to the β_{max} position with α=0 and acquire E_1 , E_2 and E_3.

Rotate the probe and acquire E_1 , E_2 and E_3 in all α-positions.

Calculate the squared yaw factor k_1^2 , k_2^2 and k_3^2 and pitch factors for sensor *1* , *2* and *3* in each position using the equations in the Theoretical part, chapter YY.

Calculate the average of the k^2- and h^2-factors and use them as sensitivity factors for the three sensors.

Note: *Directional calibration normally only needs to be carried out once in a probe's lifetime, as it depends only on the geometry, which will not change in use.*

8. DATA CONVERSION

It is advised to define the data conversion prior to running the experiment. Data conversion transforms the CTA voltages into calibration velocities in m/s by means of the calibration transfer function. Multi-sensor probes are furthermore decomposed into velocity components in the probe coordinate system. If it differs from the laboratory coordinate system, the velocity components are finally transformed into the laboratory coordinate system.

Data conversion consists of the following processes:

1. Re-scaling of acquired CTA output voltages (raw data)	Only if Signal Conditioner gain and offset have been applied.
2. Temperature correction	Only if sensor temperature has been kept constant during experiment (no overheat adjust).
3. Linearisation	Only if data reduction in amplitude domain is required.
4. Decomposition into velocity components	Only for X-probes and Tri-axial probes.

Commercial CTA application software contains modules for data conversion, where raw data are converted into velocity components according to the scheme above. Unless special conditions prevail, it is recommended to use such dedicated software packages.

8.1.1 Re-scaling:

When a CTA signal has been subject to a DC-offset and amplification between overheat setup and calibration, it has to be re-scaled before it can be linearised.

Re-scaling of CTA-signals:

Calculate the re-scaled voltage E from the acquired voltage E_a:

$$E = \frac{E_a}{Gain} - E_{offset}$$

8.1.2 Temperature correction:

If the overheat ratio has *not* been adjusted prior to the data acquisition, the CTA output voltage must be corrected for possible temperature variations before conversion. The fluid temperature needs then to be acquired along with the CTA signal.

Temperature correction of CTA voltages:

Acquire the fluid temperature, T_a , together with the CTA voltage, E_a.

Calculate the corrected CTA voltage, E_{corr} ,from:

$$E_{corr} = \left(\frac{T_w - T_0}{T_w - T_a} \right)^{0.5} \cdot E_a \qquad [60]$$

where:
E_a = acquired voltage
T_w = sensor hot temperature = $\alpha / a_0 + T_0$
T_0 = ambient reference temperature related to the last overheat setup before calibration
T_a = ambient temperature during acquisition

This expression can be used for moderate temperature changes in air %±5 °C. The useful range may be expanded by reducing the exponent n from 0.5 to 0.4 or 0.3.

8.1.3 Conversion into calibration velocities (linearisation)

The CTA voltages are converted into velocities by inserting the acquired voltages into the calibration transfer functions after re-scaling and temperature correction, if needed. The simplest and most accurate transfer function is the polynomial, at least in the case of a wide dynamic velocity range.

The velocities are calculated as if the velocity attacked the probe under the same angle during measurement as during calibration.

Polynomial linearisation of CTA voltages:

Insert the acquired CTA voltage (after possible corrections) into the polynomial:
Create a polynomial trend line of 4th order:

$$U = C_0 + C_1 E_{corr} + C_2 E_{coor}^{\ 2} + C_3 E_{corr}^{\ 3} + C_4 E_{corr}^{\ 4}$$

where C_0 to C_4 are the calibration constants.

Note: *Do not use the polynomial linearisation function outside the calibration range, as it may oscillate.*

Power law linearisation of CTA voltages:

Insert the acquired CTA voltage (after possible corrections) into the function:

$$U = \left(\frac{E^2 - A}{B} \right)^{\frac{1}{n}}$$

where A, B and n are the calibration constants.

8.1.4 X-probe decomposition into velocity components U and V

In 2-D flows measured with X-probes, the calibrated velocities together with the yaw and coefficients k^2 are used as intermediate results to calculate the velocity components U and V in the probe coordinate system.

The yaw coefficients for the two sensors may be the manufacturer's default values, or if higher accuracy is required they are determined by directional calibration of the individual sensor. In simple cases, the coefficients may be neglected.

Decomposition of X-probe voltages into U and V:

Calculate the calibration velocities U_{cal1} and U_{cal2} using the linearisation functions for sensor 1 and 2.

Decomposition with yaw coefficients k_1 and k_2 :

Calculate the velocities U_1 and U_2 in the *wire-coordinate system* (1,2) defined by the sensors using the two equations:

$$k_1^2 \cdot U_1^2 + U_2^2 = \frac{1}{2} \cdot \left(1 + k_1^2\right) \cdot U_{cal1}^2$$

$$U_1^2 + k_2^2 U_2^2 = \frac{1}{2} \cdot \left(1 + k_2^2\right) \cdot U_{cal2}^2$$

which gives:

$$U_1 = \frac{\sqrt{2}}{2} \cdot \sqrt{\left(1 + k_2^2\right) \cdot U_{cal2}^2 - k_2^2 \cdot U_{cal1}^2}$$

$$U_2 = \frac{\sqrt{2}}{2} \cdot \sqrt{\left(1 + k_1^2\right) \cdot U_{cal1}^2 - k_1^2 \cdot U_{cal2}^2}$$

Calculate the velocities U and V in the probe coordinate system *(X,Y)* from:

$$U = \frac{\sqrt{2}}{2} \cdot U_1 + \frac{\sqrt{2}}{2} \cdot U_2$$

$$V = \frac{\sqrt{2}}{2} \cdot U_1 - \frac{\sqrt{2}}{2} \cdot U_2$$

Manufacturer's (Dantec Dynamics) default values for Yaw-coefficients, k^2:

	$k_1^2 = k_2^2$
Miniature wire probes:	0.04
Gold-plated wire probes:	0.0225
Fiber-film probes for air:	0.04

8.1.5 Tri-axial probe decomposition into velocity components U, V and W

In a 3-D flows measured with a Tri-axial probe the calibration velocities are used together with the yaw and pitch coefficients k^2 and h^2 to calculate the three velocity components U, V and W in the probe coordinate system (X,Y,Z).

The yaw and pitch coefficients for the three sensors may be the manufacturer's default values, or if higher accuracy is required they are determined by directional calibration of the individual sensors.

Decomposition of Tri-axial probe voltages into U, V and W:

Calculate the calibration velocities U_{cal1} , U_{cal2} U_{cal3} using the linearisation functions for sensor 1, 2 and 3.

Decomposition with individual yaw and pitch coefficients:

Calculate the velocities U_1 , U_2 and U_3 in the *wire-coordinate system* (1,2,3) defined by the sensors using the three quations:

$$k_1^2 \cdot U_1^2 + U_2^2 + h_1^2 \cdot U_3^2 = \left(1 + k_1^2 + h_1^2\right) \cdot \cos^2 54.74 \cdot U_{cal1}^2$$
$$h_2^2 \cdot U_1^2 + k_2^2 \cdot U_2^2 + U_3^2 = \left(1 + k_2^2 + h_2^2\right) \cdot \cos^2 54.74 \cdot U_{cal2}^2$$
$$U_1^2 + h_3^2 \cdot U_2^2 + k_3^2 U_3^2 = \left(1 + k_3^2 + h_3^2\right) \cdot \cos^2 54.74 \cdot U_{cal3}^2$$

With the k^2=0.0225 and , h^2=1.04 default values for a tri-axial wire probe, the velocities U_1, U_2 and U_3 in the wire coordinate system becomes:

$$U_1 = \sqrt{-0.3477 \cdot U_{cal1}^2 + 0.3544 \cdot U_{cal2}^2 + 0.3266 \cdot U_{cal3}^2}$$
$$U_2 = \sqrt{0.3266 \cdot U_{cal1}^2 - 0.3477 U_{cal2}^2 + 0.3544 \cdot U_{cal3}^2}$$
$$U_3 = \sqrt{0.3544 \cdot U_{cal1}^2 + 0.32663 \cdot U_{cal2}^2 - 0.3477 \cdot U_{cal3}^2}$$

Calculate the U, V and W in the probe coordinate system:

$$U = U_1 \cdot \cos 54.74 + U_2 \cdot \cos 54.74 + U_3 \cdot \cos 54.74$$
$$V = -U_1 \cdot \cos 45 - U_2 \cdot \cos 135 + U_3 \cdot \cos 90$$
$$W = -U_1 \cdot \cos 114.09 - U_2 \cdot \cos 114.09 - U_3 \cdot \cos 35.26$$

Manufacturer's (Dantec Dynamics) default values for k^2 and h^2:

	k^2	h^2
Gold-plated wire sensors:	0.0225	1.04
Fiber-film sensors for air:	0.04	1.20

9. DATA ACQUISITION

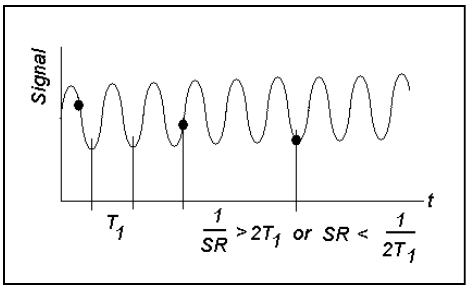
The CTA signal is a continuos analogue voltage. In order to process it digitally it has to be sampled as a time series consisting of discrete values digitized by an analogue-to-digital converter (A/D board).

The parameters defining the data acquisition are the *sampling rate SR* and the *number of samples, N*. Together they determine the *sampling time* as *T=N/SR*. The values for *SR* and *N* depend primarily on the specific experiment, the required data analysis (time-averaged or spectral analysis), the available computer memory and the acceptable level of uncertainty. Time-averaged analysis, such as mean velocity and rms of velocity, requires non-correlated samples, which can be achieved when the time between samples is at least two times larger than the integral time scale of the velocity fluctuations. Spectral analysis requires the sampling rate to be at least two times the highest occurring fluctuation frequency in the flow. The number of samples depends on the required uncertainty and confidence level of the results.

Time avaraged analysis:

Estimate the following expected quantities in the flow:

velocity U [m/s] , turbulence intensity Tu [%] , and integral time-scale T_I [seconds] (see *Chapter 10.2*).



Select the wanted uncertainty and confidence level:

uncertainty u, %, in U_{mean}

confidence level (1-a), %

Calculate the sampling rate *SR:*

$$SR \leq \frac{1}{2T_1} \quad \text{(gives uncorrelated samples)}$$

Calculate the number of samples *N:*

$$N = \left(\frac{1}{u} \cdot \left(\frac{z_a}{2} \right) \cdot Tu \right)^2$$

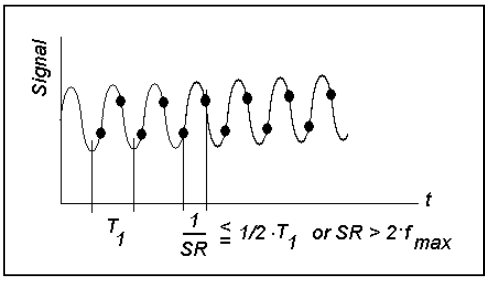
$z_a/2$	(1-a) %
1.65	90
1.96	95
2.33	98

where $z_a/2$ is a variable related to confidence level (1-a) of the Gaussian probability density function *p(z).*

Sampling rate SR for time spectral analysis:

Calculate the sampling rate *SR:*

$SR \geq 2 \cdot f_{\max}$ (Nyquist critrium with f_{max} based on an oversampled time series.), or



$SR = 2 \cdot f_{cut-off}$ (based on low-pass filter setup), or

$SR = 2.5 \cdot f_{cut-off}$ (the factor 2.5 adopts to a non-ideal low-pass filter, which does not set the signal to zero at the cut-off frequency [57]).

10. DATA ANALYSIS

As the CTA signal from a turbulent flow will be of random nature, a statistical description of the signal is necessary. The time series can be analysed or reduced either in the amplitude domain, the time domain or in the frequency domain. The following procedures all require stationary random data.

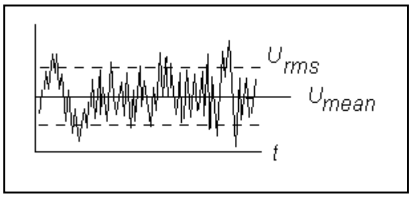
CTA application software contains modules that perform the most common data analysis, as defined below. The standard procedure is to select the wanted analysis and apply it to the actual time series. The reduced data will then be saved in the project and be ready for graphical presentation or for exporting to a report generator.

10.1 Amplitude domain data analysis

The amplitude domain analysis provides information about the amplitude distribution in the signal. It is based on one or more time series sampled on the basis of a single integral time-scale in the flow. A velocity time series represents data from one sensor, converted into a velocity component in engineering units.

A *single* velocity time series provides mean, mean square and higher order moments.

Moments based on a single time series:

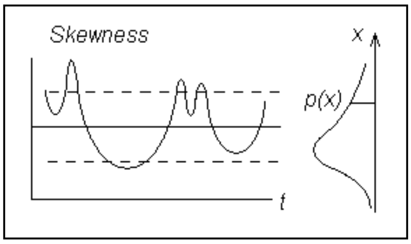


Mean velocity: $$U_{mean} = \frac{1}{N}\sum_{1}^{N} U_i$$

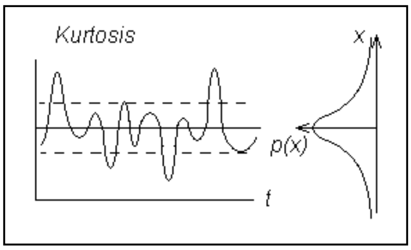
Standard deviation

of velocity: $$U_{rms} = \left(\frac{1}{N-1}\sum_{1}^{N}(U_i - U_{mean})^2\right)^{0.5}$$

Turbulence intensity: $$Tu = \frac{U_{rms}}{U_{mean}}$$



Skewness: $$S = \sum_{1}^{N}\frac{(U_i - U_{mean})^3}{N \cdot \sigma^3}$$



Kurtosis (or flatness): $$K = \sum_{1}^{N}\frac{(U_i - U_{mean})^4}{N \cdot \sigma^4}$$

where the variance σ is defined as:

$$\sigma = \left(\sum_{1}^{N}\frac{(U_i - U_{mean})^2}{N-1}\right)^{0.5}$$

The Skewness is a measure of the lack of statistical symmetry in the flow, while the Kurtosis is a measure of the amplitude distribution (flatness factor).

Two simultaneous velocity time series provide cross-moments (basis for Reynolds shear stresses) and higher order cross moments (lateral transport quantities), when they are acquired at the same point. If they are acquired at different points they provide spatial correlations, which carries information about typical length scales in the flow.

Moments based on two time series:

Reynolds shear stresses:

$$\overline{uv} = \frac{1}{N}\sum_{1}^{N}\left(U_i - U_{mean}\right)\cdot\left(V_i - V_{mean}\right)$$

$$\overline{uw} = \frac{1}{N}\sum_{1}^{N}\left(U_i - U_{mean}\right)\cdot\left(W_i - W_{mean}\right)$$

$$\overline{vw} = \frac{1}{N}\sum_{1}^{N}\left(V_i - V_{mean}\right)\cdot\left(W_i - W_{mean}\right)$$

Lateral transport quantities:

$$\overline{u^2 v} = \frac{1}{N}\sum_{1}^{N}\left(U_i - U_{mean}\right)^2\cdot\left(V_i - V_{mean}\right)$$

$$\overline{u^2 w} = \frac{1}{N}\sum_{1}^{N}\left(U_i - U_{mean}\right)^2\cdot\left(W_i - W_{mean}\right)$$

$$\overline{v^2 u} = \frac{1}{N}\sum_{1}^{N}\left(V_i - V_{mean}\right)^2\cdot\left(U_i - U_{mean}\right)$$

$$\overline{v^2 w} = \frac{1}{N}\sum_{1}^{N}\left(V_i - V_{mean}\right)^2\cdot\left(W_i - W_{mean}\right)$$

$$\overline{w^2 v} = \frac{1}{N}\sum_{1}^{N}\left(W_i - W_{mean}\right)^2\cdot\left(V_i - V_{mean}\right)$$

10.2 Time-domain data analysis

The most often applied time-domain statistic is the auto-correlation function, Rx(t), from which the integral time-scale can be calculated. This is an important quantity, as it defines the time interval between statistically uncorrelated samples.

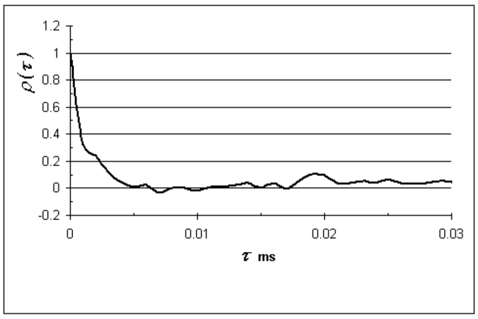
In most CTA application software with data reduction features, the auto-correlation coefficient function is normally calculated and graphically displayed. It starts with the value 1 at time zero, drops down to zero and normally continues oscillating around zero. A reasonable estimate of T_I is the time it takes the coefficient to drop from the unity start value to zero.

Auto-correlation function and integral time-scale:
Requires a long time series *x(t)* sampled according to the Nyquist criteria.
Auto-correlation function:

$$R_x(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t) \cdot x(t+\tau) \cdot dt$$

Integral time-scale: $$T_I = \int_0^\infty \rho_x(\tau) \cdot d\tau$$

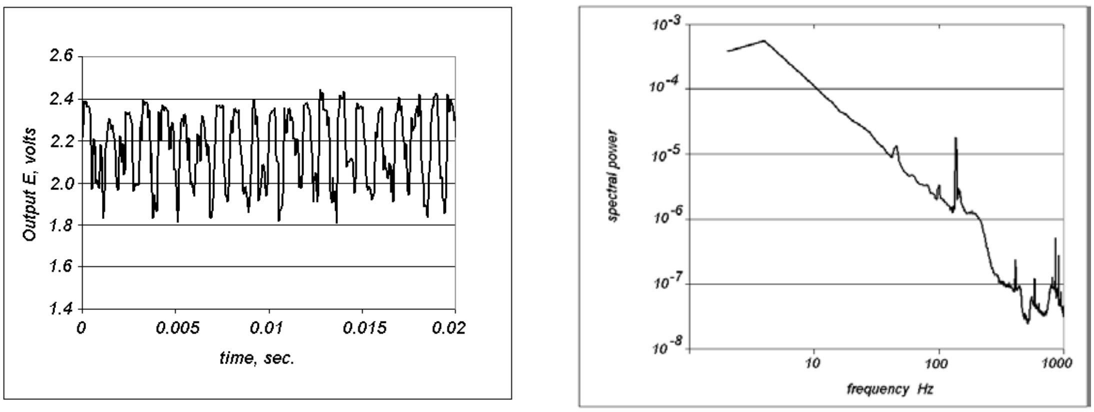
where the auto-correlation coefficient is defined as: $$\rho_x(\tau) = \frac{R_x(\tau)}{R_x(0)}$$



Note: Auto-correlation can be made on non-linearised raw data.

10.3 Spectral-domain data analysis

Spectral analysis can be used to provide information about how the energy of the signal is distributed with respect to frequency.



Power spectrum of the flow behind a circular cylinder.

The analysis can be performed on raw, non-linearised signals, provided they are sampled according to the Nyquist criteria. The accuracy of the spectra depends on the algorithm used and on the number of samples, which normally must be high. There exist a number of different algorithms for the calculation of spectra mostly based on Fourier transforms, which produce values of discrete frequencies within sub-records of the signal. Normally CTA application software contains routines for spectral analysis.

11. RUNNING AN EXPERIMENT

The experiment can be executed when system setup, probe calibration, data acquisition setup, and data reduction (algorithms for data analysis) have been established. Prior to running the experiment it is advised to verify the complete setup by performing measurements in a known part of the flow. Probe calibrations before and after the experiment are advisable in order to check probe stability.

11.1 General procedure:

Before the experiment can start, the measuring system must be configured, the CTA bridge and Signal Conditioner set up and the data acquisition and data reduction defined in accordance with the flow characteristics.

Running an experiment, general procedure:

Calibrate the probe(s). It is always recommended to calibrate the probe immediately before and after an experiment.

Verify the setup:

- *Position* the probe in a part of the flow, which is reasonably well known, and acquire data in one or more points.
- *Perform* data reduction in both amplitude and spectral domain (*Umean*, *Urms* and *Power spectra* as minimum).
- *Compare* with expected values.
- *Check* stability of statistics by comparing results from data records of different lengths.
- *Adjust* data acquisition setup (sample rate SR and number of samples N), if need be.

Position the probe in the flow together with a temperature probe, if temperature correction of data is required.

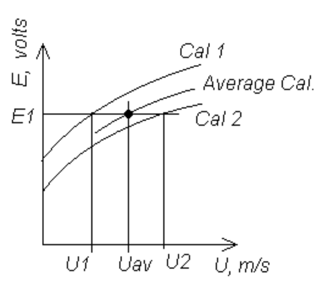
Move the probe to the proper position in the traverse grid (if employed).

Acquire the CTA output voltages together with other signals needed for correction or control and move to next position.

Analyse (reduce) data before the experiment is shut down, if possible.

Re-calibrate the probe after the experiment and compare with previous calibration. This can be done in practice by reducing the same raw data set by means of the two calibrations and compare the results.

Note: *If the calibration drifts linearly with time during an experiment, the drift may be compensated for by using a new transfer function based on the averages of velocites calculated from identical voltage values inserted into the transfer functions from the first and the second calibrations.* $U_{av}=(U_1+U_2)/2=(f_{cal1}(E_1)+f_{cal2}(E_1))/2$.



11.2 Experimental procedure in non-isothermal flows:

As the CTA anemometer is sensitive to variations in ambient temperature, as well as velocity, it is often necessary to make special precautions in non-isothermal flows in order to eliminate errors in the measured velocity due to temperature variations. The error in thevelocity measured with a wire probe in air is approximately 2% per 1 °C change in air temperature. The measured velocity decreases with increasing temperature and vice versa.

This error may be avoided by setting up the CTA bridge and correcting the data in one of the following ways:

1. Operate the probe with a ***constant sensor temperature*** (obtained by leaving the decade resistor in the CTA fixed during calibration and data acquisition) and correct the CTA voltage before linearisation and data reduction. The ambient temperature must be acquired simultaneously with a temperature sensor, which is fast enough to follow the temperature variations.
2. Operate the probe with a ***constant overheat ratio*** (obtained by adjusting the overheat ratio before each calibration and data acquisition). This requires that the ambient temperature remains constant (or nearly constant) during the time it takes to perform a data acquisition.

CTA setup and Data conversion in non-isothermal flows:

Constant sensor temperature (fixed decade resistance) with temperature correction of data:

Adjust the overheat ratio a at a known ambient temperature T_{ref}.
Leave the CTA bridge and make no more overheat adjustments during the experiment or during recalibrations (disable “automatic overheat adjust” in StreamLine).
Calibrate the probe and measure temperature in each calibration point. Correct the raw voltages to T_{ref} and make a curve fit.
Position the probe in the test rig and acquire the CTA voltages, E_a ,and ambient temperature, T_a ,as close to the probe as possible.
Correct the raw CTA voltages (see ***Chapter 8.1.2***) before further conversion (linearisation) and reduction.

Constant overheat ratio without temperature correction of data:

Adjust the overheat ratio, a, at a known ambient temperature T_a.(Enable “Automatic overheat adjust” in StreamLine).
Calibrate the probe at T_a and make a curve fit.
Position the probe in the test rig and re-adjust the overheat ratio, a, at the new ambient temperature.
Acquire the CTA voltages E.
Convert (linearise) and reduce the raw CTA voltages without any prior corrections.

12. DISTURBING EFFECTS

Measurements with hot-wire anemometers are influenced by a number of disturbing effects. In fact any change in a parameter that enters into the mechanism of heat transfer from the wire to its surroundings may act as a disturbing effect and reduce the accuracy of the measurement result. The effects may be related to the flow medium and sensor condition. For special effects from e.g. natural convection, wall nearness etc. please refer to the CTA literature.

12.1 Flow related effects:

12.1.1 Temperature:

Temperature variations are normally the most important error source, as the heat transfer is directly proportional to the temperature difference between the sensor and the fluid. For a wire probe operated under normal conditions, the error in measured velocity is approx. 2% per 1 °C change in temperature. For film probes in water the error may be up to 10% per 1 °C. In both cases the measured velocity decreases with increasing ambient temperture.

Different precautions can be taken in order to avoid systematic conversion errors when probe voltages are converted into velocities. One solution is to readjust the overheat resistor to the changed temperature, so that overheat ratio is kept constant from calibration to measurement. Another solution is to leave the overheat resistor constant, measure the temperature and correct the probe voltage. See *Chapter 10.2 Experimental procedure in non-isothermal flows*. A special case is the temperature-compensated wire probe with build-in temperature-sensitive overheat resistor which measures velocity independent of temperature variations.

12.1.2 Pressure:

Pressure variations:

Pressure variations enter directly into the heat transfer equation, as the probe in fact measures the mass flux $\rho \cdot U$. Normally probes are calibrated against velocity only. As pressure variations from calibration to experiment and during an experiment are normally small, the pressure influence in the CTA measurements is normally neglected.

Pressure range:

The lower limit for pressures, at which a probe can be used, are determined by the slip-flow conditions defined by the Knudsen number *Kn* (ratio between molecular mean free path and sensor diameter should be smaller than 0.01). For a 5 μm wire probe at atmospheric conditions Kn=0.2. Provided density variations are small the flow is considered to be a continuum, and pressure effects are normally neglected.

12.1.3 Composition:

In most cases the fluid composition remains constant during calibration and experiment, and it is of no importance. In air one normally experiences variations in water vapour content (humidity). The influence is very small, less than 1%, and is almost always neglected.

12.2 Sensor conditions.

12.2.1 Contamination:

Particle contamination reduces the heat transfer resulting in a downward drift in the calibration. The influence of particle contamination increases with decreasing sensor surface. Wire probes with 5 µm sensors can be used without problems in normal laboratory air, if they are recalibrated at regular intervals. Fiber-film probes are less susceptible and can be used, e.g. in outdoor applications without problems. If the calibration drifts significantly, it may be necessary to clean the sensor.

Contamination is a much bigger problem in liquid flows than in gas flows. This means that film probes with non-cylindrical sensors should always be preferred for fiber-film probes whenever possible, unless a careful filtering of the water is carried out.

12.2.2 Sensor Robustness:

Normally all probes will survive almost any experiment, when safely placed in the test rig. By far the most damages to sensors happen during handling. It is, however, wise to take the robustness of the probe into consideration before it is selected for a particular application. In general the robustness increases with the size of the sensor.

12.2.3 Sensor orientation:

The effect of sensor orientation is neglectible as long as the sensor is placed identically with respect to the flow during calibration and measurement. The misalignement is normally so small that it may be neglecetd as an error source.

13. UNCERTAINTY OF CTA MEASUREMENTS

Current standards refer to the ISO uncertainty model which combines uncertainty contributions $U(y_i)$ from each individual input variable x_i into a total uncertainty at a given confidence level. The output variable is defined as $y_i=f(x_i)$.

The relative standard uncertainty $u(y_i)$ is a function of the standard deviation of the input variance:

$$u(y_i)=\frac{1}{y_i}\cdot S\cdot\left(\frac{\Delta x_i}{k_i}\right)$$

where $S=\partial y_i/\partial x_i$ is the sensitivity factor and k_i is the coverage factor related to the distribution of the input variance (gaussian, rectangular etc.).

As most engineering applications are assumed to have a Gaussian error distribution, the 95% confidence level normally required is achieved by multiplying the standard uncertainty with the coverage factor k=2. The total relative expanded uncertainty then becomes:

$$U(tot)=2\cdot\sqrt{\sum u(y_i)^2}$$

The uncertainty of the results obtained with the CTA anemometer is a combination of the uncertainties of the individually acquired voltages converted into velocity and the uncertainty of the statistical analysis of the velocity series. The following chapters provide a guide on how to estimate the uncertainties of CTA measurements under normal conditions.

13.1 Uncertainty of a velocity sample.

This chapter presents the uncertainty of a single velocity sample acquired via an A/D from a CTA anemometer with a single-sensor probe. The uncertainty of each individual velocity sample is determined by non-statistical means based on detailed knowledge about the *instrumentation*, *calibration equipment* and *experimental conditions*. The uncertainties presented below are *relative expanded* uncertainties.

13.1.1 Anemometer:

Drift, noise, repeatability and frequency response:

Commercially available anemometers have low drift, low noise and good repeatability so that these factors do not add significantly to the uncertainty in comparison with other error sources. In certain applications, e.g. dissipation measurements, the high frequency noise of the anemometer may be of importance.

The frequency characteristic of the anemometer will not add to the uncertainty, when the frequencies in the flow are below approximately 50% of the cut-off frequency (from the square wave test), as the characteristic is normally flat up to this point.

13.1.2 Calibration/conversion:

Calibration equipment:

The calibration, whether it is performed with a dedicated calibrator or with a pitot-static tube as reference, constitutes a major source of uncertainty. The error is *stochastic* with a normal distribution and the *relative standard* uncertainty can be expressed as:

$$U(U_{cal}) = \frac{1}{100} \cdot STDV(U_{calibrator}(\%))$$

The calibrator uncertainty is often given as a *relative standard* uncertainty, a_{cal}, in percent plus a constant contribution b_{cal} in m/s :

$$STDV(U_{calibrator}) = \pm a(\%) + bcal(m/s)$$

The constant contribution b_{cal} may be normally neglected at velocities above 5 m/s.

	a_{cal} %	b_{cal} m/s
Good dedicated calibrator	±1	±0.02
Pitot-static tube with calibrated micro-manometer (U_{cal}>2 m/s)	±2%	

Linearisation (Conversion):

The linearisation uncertainty is related to the curve fitting errors. It is stochastic with a normal distribution and its *relative standard* uncertainty can be calculated from:

$$U(U_{lin}) = \frac{1}{100} \cdot STDV(\Delta U_{lin}(\%))$$

where STDV(ΔU_{lin}) is the standard deviation of the curve fitting errors in the calibration points in %.

13.1.3 Data acquisition related uncertainties

A/D board resolution

The resolution uncertainty is stochastic with a square distribution and its *relative standard* uncertainty can be expressed as:

$$U(U_{res}) = \frac{1}{\sqrt{3}} \cdot \frac{1}{U} \cdot \frac{E_{AD}}{2^n} \cdot \frac{\partial U}{\partial E}$$

where E_{AD} is the A/D board input range, n is its resolution in bits, U the velocity and $\partial U/\partial E$ is the slope (sensitivity factor) of the inverse calibration curve, $U=f(E)$.

13.1.4 Uncertainties related to experimental conditions

Probe positioning

The positioning uncertainty relates to the alignment of the probe in the experimental setup after calibration. The uncertainty is stochastic with a square distribution and its *relative standard* uncertainty can be expressed as:

$$U(U_{pos}) = \frac{1}{\sqrt{3}} \cdot (1 - \cos\theta)$$

Normally a probe can be positioned with an uncertainty $\Delta\theta$=1°.

Temperature variations

Temperature variations from calibration to experiment or during an experiment introduce systematic errors. If not corrected, a change in temperature changes the sensor over-temperature and contributes as a stochastic uncertainty with rectangular distribution. The *relative standard* uncertainty is:

$$U(U_{temp}) = \frac{1}{\sqrt{3}} \cdot \frac{1}{U} \cdot \frac{1}{T_w - T_0} \cdot \left(\frac{A}{B} \cdot U^{-0.5} + 1 \right)^{0.5}$$

where T_w is the sensor temperature, T_0 the ambient reference temperature, and ΔT is the difference between the ambient reference temperature and the temperature during the measurement.

This estimate is based on the power law calibration function:

$$E^2 = (T_w - T_0) \cdot \left(A + B \cdot (U_{cal})^{0.5} \right) = (T_w - T_0) \cdot \left(A + B_1 \cdot (\rho \cdot U)^{0.5} \right)$$

Since the velocity U_{cal} actually represents the mass flux, ρU, variations in density, ρ, with temperature will add to the uncertainty, if not accounted for. In gases, this gives following *relative standard* uncertainty:

$$U(U_{\rho,T}) = \frac{1}{\sqrt{3}} \cdot \Delta\rho,_T = \frac{1}{\sqrt{3}} \cdot \frac{\Delta T}{273}$$

Ambient pressure variations

Ambient pressure changes also influence the density and hence the calculated velocity. It contributes as a stochastic uncertainty with rectangular distribution with following *relative standard* uncertainty:

$$U(U_{\rho,P}) = \frac{1}{\sqrt{3}} \cdot \left(\frac{P_0}{P_0 + \Delta P} \right)$$

Gas composition, humidity

Under normal conditions changes in gas composition are mainly caused by changes in humidity. The uncertainty is stochastic with a rectangular distribution having a *relative standard* contribution of:

$$U(Uhum) = \frac{1}{\sqrt{3}} \cdot \frac{1}{U} \frac{\partial U}{\partial P_{wv}} \cdot \Delta P_{wv}$$

The influence on the heat transfer is very small, $\partial U/\partial P_{wv} \approx 0.01 \cdot U$ per 1 kPa change in water vapour pressure P_{wv}.

13.1.5 Velocity sample uncertainty

The relative expanded uncertainties on a single velocity sample obtained with a single-sensor hot-wire probe in air, can be summarized in the following table:

Input data are: T_w-T_0=200 °C, U=15 m/s, A=1.396, B=0.895, $\partial U/\partial E$=46.5 m/s/volt

Source of uncertainty	Input varians	Typical value	Relative output varians	Typical value	Cover-age factor	Relative standard uncer-tainty
	Δx_i	Δx_i	$\frac{1}{U} \cdot \Delta y_i$	$\frac{1}{U} \cdot \Delta y_i$	k	$\frac{1}{k} \cdot \frac{1}{U} \cdot \Delta y_i$
Calibrator	ΔU_{cal}	1%	$2 \cdot \mathrm{STDV}(100 \cdot \Delta U_{cal})$	0.02	2	0.01
Linearisation	ΔU_{fit}	0.5%	$2 \cdot \mathrm{STDV}(100 \cdot \Delta U_{fit})$	0.01	2	0.005
A/D resolution	E_{AD} n	10 volts 12 bit	$\frac{1}{U} \cdot \frac{E_{AD}}{2^n} \cdot \frac{\partial U}{\partial E}$	0.000 8	√3	0.0013
Probe positioning	θ	1 °	$1\text{-}\cos\theta$	0.000 15	√3	≈0
Temperature variations[1)]	ΔT	1 °C	$\frac{1}{U} \cdot \frac{\Delta T}{(T_w - T_0)} \cdot \left(\frac{A}{B} \cdot U^{-0,5} + 1\right)$	0.013	√3	0.008
Temperature variations[2)]	ΔT	1 °C	$\frac{\Delta T}{273}$	0.004	√3	0.002
Ambient pressure	ΔP	10 kPa	$\frac{P_0}{P_0 + \Delta P}$	0.01	√3	0.006

Humidity	ΔP_{wv}	1 kPa	$\frac{1}{U} \cdot \frac{\partial U}{\partial P_{wv}} \cdot \Delta P_{wv}$	0.000 6	√3	≈0
Relative expanded uncertainty[3]: U(Usample) = $2 \cdot \sqrt{\sum \left(\frac{1}{k} \cdot \frac{1}{U} \cdot \Delta y_i \right)^2}$ = 0.030 = 3 %						

Table 1. Error sources and uncertainties for a single velocity sample acquired with a CTA under typical experimental conditions including calibrator uncertainty.

1) Uncertainty due to change in sensor overtemperature alone.

2) Uncertainty due to change in air density with temperature alone.

3) The two uncertainties from temperature variations are inter-correlated and should be added arithmetically before they are added geometrically to the other uncertainties.

From above example it appears that the voltage from a CTA with a wire probe can be acquired and converted into a velocity sample with an uncertainty of approximately 1 % with a 95% confidence interval with reference to the calibration and neglecting the uncertainty of the calibrator itself. When the uncertainty of calibrator is included, the uncertainty of a velocity sample increases to typically 3%. The major contributions come from the calibrator, temperature variations in the flow and the linearisation (curve fitting). Variations in atmospheric pressure may also play a role.

13.2 Uncertainty of reduced data.

The uncertainty of reduced data (mean velocity, standard deviation of velocity etc.) depends on the uncertainty of the individual samples as described in chapter 11.1 and on how true the data represents the flow. As the data presents a random process the choice of sampling rate and number of samples is most important for the uncertainty due to the sampling process. The criteria for this choice are shortly described in chapter 7, where it is demonstrated how the number of samples can be calculated on the basis of known turbulence intensity, and the required uncertainty and confidence level.

For further reading please consult the literature.

14. Advanced topics.

Very low velocities.

At very low velocities the heat transfer from the wire is governed by natural convection. This means that the cooling not only depends on the magnitude of the velocity but also its orientation with respect to the gravity field. The influence of natural convection starts around 0.2 m/s for wire probes and takes over completely around 0.03-0.04 m/s. In this range it is important that the probe has the same orientation with respect to the velocity field during calibration and measurement [22].

High velocities, compressible flows.

At high velocities the flow becomes compressible and effects from compressibility should be taken into account. In practice this means that pressure and velocity should be measured simulatneously. The correction is quite complicated and is very often neglected [33],[48], [55].

Rarified flows (low pressures).

When the pressure decreases the mean free path of the molecules increases. If the Knudsen number Kn (wire diameter divided by free mean path) gets smaller than 100, the heat transfer becomes a function of both velocity and Knudsen number (or pressure). For a 5 micrometer diameter wire the Kn is around 100 at atmospheric conditions. If lower pressures occur, it should be considered to use fibre-film probes instead of wire probes [8].

Wall effects.

When the wire is placed close to a solid wall, heat will be conducted through the flowing medium to the wall. If not corrected for this will cause the velocity to be measured too high. The wall influence starts at $y+ \leq yU\tau/\nu = 3.5$ (y= distance to the wall, $U\tau$ =friction velocity and ν=kinematic viscosity). The critical wall distance is typically 0.1 to 0.2 mm depending on free stream velocity [53], [62], [22].

Very high turbulence, revering flows.

If the turbulence is very high, above 30% or more, or in reversing flows, where the velocity vector falls outside the opening angle of the sensor array, the results will be incorrect. Such flows can be measured correctly with flying hot-wire systems, where the probe is moved through the flow field with a speed high enough to move the resulting velocity vector inside the opening angle. After linearisation the flying speed is subtracted from the longitudinal velocity component [52], [56].

Wall shear stress.

Wall shear stress can be measured with flush mounting film probes mounted in the wall. The heat transfer can then be expressed as a function of the wall shear stress. The probes have to be calibrated in a known shear. It should be noted that the secondary heat transferred to the wall changes the frequency response of wall mounted probes as compared to freely mounted film probes [25], [37].

Two-phase flows.

As the heat transfer is much bigger in liquids than in gases, a hot wire (or hot-film) will clearly distinguish between liquid and gas phase. This can be utilised to measure the passage of for example air bubbles in water [20].

Binary mixtures.

The heat transfer to gases depends to some extent on the heat conductivity of the gas. The heat transfer from a wire can therefore be used to measure the concentration in binary mixtures. This is done in practice by placing the wire in a sonic nozzle (aspirating probe), where the probe is exposed to a constant velocity independent of the free stream velcocity and therefore primarily responds to changes in heat conductivity [44].

15. THE CTA ANEMOMETER , BASIC PRINCIPLES

The hot-wire anemometer was introduced in its original form in the first half of the 20th century. A major breakthrough was made in the fifties, where it became commercially available in the presently used constant temperature operational mode (CTA). Since then it has been a fundamental tool for turbulence studies. The measurement of the instantaneous flow velocity is based upon the heat transfer between the sensing element, for example a thin electrically heated wire or a metal film, and the surrounding fluid medium. The rate of heat loss depends on the excess temperature of the sensing element, its physical properties and geometrical configuration, and the properties of the moving fluid. A hot-wire anemometer provides reliable information on the fluctuating flow component in both the space and time domains.

15.1 Characteristics of the hot-wire sensing element,

15.1.1 Static characteristics - stationary heat transfer

The relationship between the fluid velocity and the heat loss of a cylindrical wire is based on the assumption that the fluid is incompressible and that the flow around the wire is potential. When a current is passed through wire, heat is generated (I^2R_w). During equilibrium, the heat generated is balanced by the heat loss (primarily convective) to the surroundings. If the velocity changes, then the convective heat transfer coefficient will also change resulting in a wire temperature change that will eventually reach a new equilibrium with the surroundings.

The experimentally obtained static calibration curve is typically plotted as hot-wire voltage versus flow velocity. It may be described by a power law relationship given in terms of the non-dimensional parameters Reynolds number, *Re*, Nusselt number, *Nu*, and the Prandtl number, *Pr*. Emperically this type of dependency is valid for $0.01<Re<10^4$ [15]. Actually the heat loss is influenced by a number of other factors like: natural convection at very low velocities, compressibility effects at high velocities, density effects at low pressures. Please refer to the Hot-wire literature concerning these more specialised matters.

15.1.2 Dynamic characteristics, frequency limit.

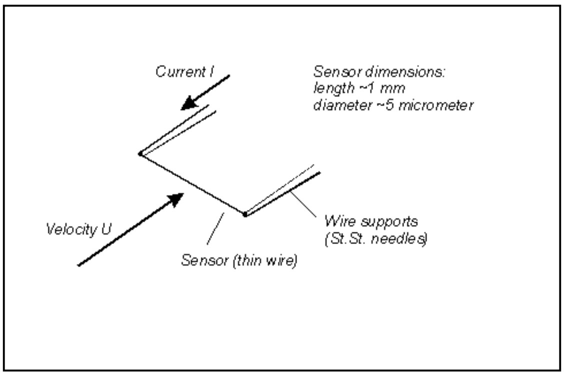
The hot-wire response can be derived from the nonstationary heat balance equation. When exposed to changes in flow velocity the wire will not react instantaneously due to its thermal inertia. This will dampen the variations in wire resistance R_w (and in wire voltage) and result in flow fluctuations being measured smaller than they actually are. The wire response alone is far too slow for most turbulence studies, and compensation in the electronics of the anemometer is therefore necessary. By using the Constant Temperature Anemometer principle, whereby a feed-back amplifier keeps the sensor resistance constant independent of variations in U, the frequency limit may be increased up to 1000 times or more [10], [12].

Governing equation:

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

$$W = Q + \frac{dQ_i}{dt}$$

W = power generated by Joule heating
$W = I^2 R_w$, recall $R_w = R_w(T_w)$
Q = heat transferred to surroundings
$Q_i = C_w T_w$ =thermal energy stored in wire
C_w = heat capacity of wire
T_w = wire temperature



Static characteristics –stationary heat transfer:

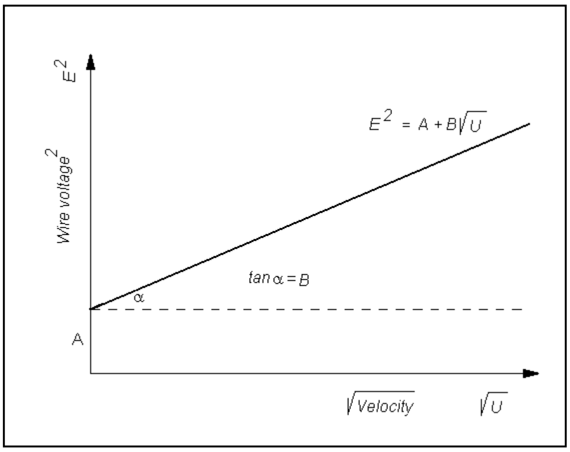
Heat storage in the wire is zero:

$$W = Q = I^2 R = hA(T_w - T_0)$$

or replacing h with Nu:

$$I^2 R_w = \frac{A}{d} Nu k_f (T_w - T_0)$$

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



In the forced convection regime (0.02<Re<140):

Reynolds number: $\mathrm{Re} = \frac{\rho \cdot U \cdot d}{\mu}$, ρ = air density, U= velocity and μ = air dynamic viscosity.

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

$I^2 R_w^2 = E^2 = (T_w - T_0)(A + BU^n)$ "King's law" [15]. The voltage is a measure of velocity U.

Dynamic characteristics- frequency limit:

Heat storage term added to the stationary heat transfer equation:

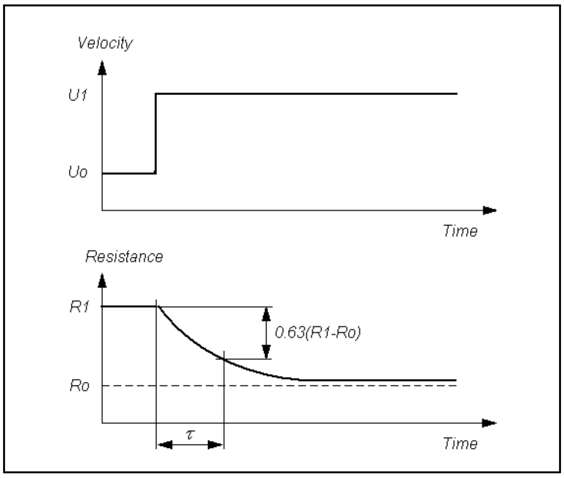
$$I^2 R_W = (R_W - R_0)(A + BU^n) + C_W \frac{dT_W}{dt}$$

or expressing T_w in terms of R_w and temperature coefficient of resistance α_0:

$$I^2 R_w = (R_w - R_0)(A + BU^n) + \frac{C_w}{\alpha_0 R_0} \frac{dR_w}{dt}$$

This differential equation has the time constant τ:

$$\tau = \frac{C_w}{\alpha_0 R_0 (A_1 + B_1 U^n - I^2)}$$



Frequency limit (3 dB amplitude damping):

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

15.2 Mechanical design of hot-wire probes

A hot-wire probe for the measurement of high frequency flow fluctuations consists of a very thin wire mounted on some kind of support. The hot-wire material is chosen so as to fulfil a number of requirements such as: high temperature coefficient of resistance, high specific resistance, high mechanical strength and ability to operate at high temperatures. Tungsten is far superior to other metals in this respect and is therefore used, whenever possible. It can be used at wire temperatures up to 300 ˚C and at velocities up to the supersonic range. Most hot-wires have a diameter of 5 µm and a length of approximately 1mm. The wire is spot-welded to needle-shaped prongs, normally made of stainless steel. The prongs are embedded in a probe body, which electrically connects to the anemometer via a probe cable.

15.3 Spatial resolution of hot-wires.

The space volume over which the hot-wire output averages depends on the wire size, its frequency limit and the flow velocity. The resolution length in the direction of the flow will be directly proportional to the mean velocity and inversely proportional to the upper frequency limit of the hot-wire inclusive of the anemometer circuit. The upper frequency limit of an anemometer should be chosen so that the resolution length in the direction of the mean flow velocity is of the same order of magnitude as the length of the wire. At 50 m/s an anemometer with a frequency limit of 25 kHz a typical wire probe will have a spatial resolution of 1 mm in the streamwise direction.

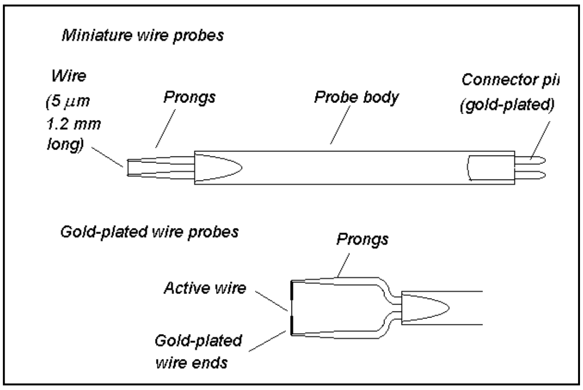
15.4 Directional sensitivity of hot-wires.

The heat transfer relation for a hot-wire, which forms basis for its static calibration, assumes that the veocity vector is directed normal to the wire. In fact the heat transfer strongly depends on the angle between the velocity vector and the wire. In the case of an ideal sensor, where there is no heat conduction to the prongs, the heat transfer varies with the cosine of the angle between the velocity and the wire normal. In reality heat is conducted to the prongs and a directional sensitivity factor k (yaw-factor), which descibes the prong interference, has to be introduced. In a 3-dimensional flow, where the velocity moves out of the wire-prong plane, the heat transfer will increase due to increased cooling of the prongs. This can be described by the pitch factor h.

Individual directional calibration of hot-wires, in addition to velocity calibrations, makes it possible to measure both velocity magnitude and direction in 2 or 3-dimensional flows using probes with 2- or 3-wires arranged in orthogonal arrays.

Probe design:

Tungsten wire is spot-welded to stainless steel prongs embedded in a ceramic tube.
Gold-plated probes have plated wire ends in order to minimise prong effects.



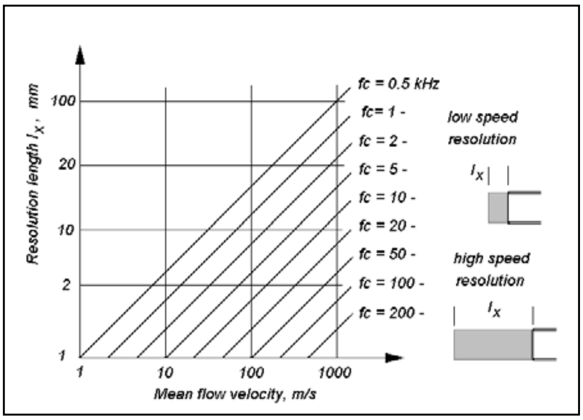
Spatial resolution:

Hot-wire resolution l_x in streamwise direction:

$$l_x = \frac{U_{mean}}{2f_{cp}} \quad [5].$$

U_{mean} = mean velocity
f_{cp} = frequency limit

High spatial resolution at high velocity requires high bandwidth



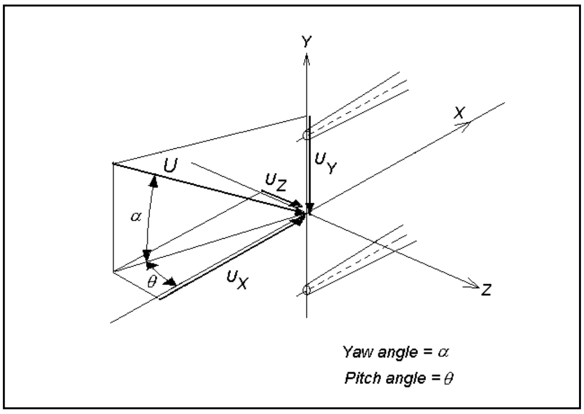
Directional sensitivity:

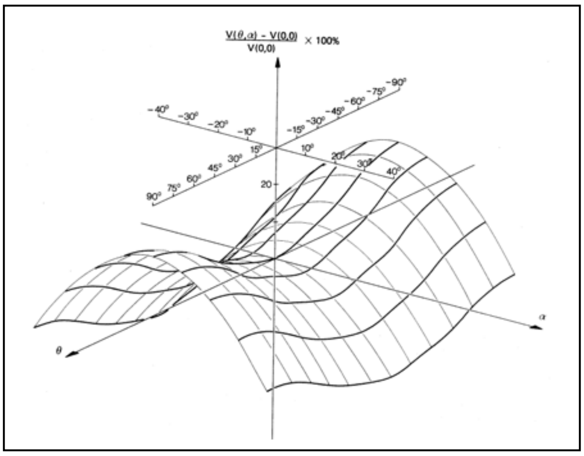
Finite wire response includes yaw and pitch Sensitivity [24], [29].:

$$U(\alpha)^2 = U(0)^2\left(\cos^2\alpha + k^2\sin^2\alpha\right) \qquad \theta = 0$$
$$U(\theta)^2 = U(0)^2\left(\cos^2\theta + h^2\sin^2\theta\right) \qquad \alpha = 0$$

General response in 3-D flows:

$$U_{eff}^{\ 2} = U_x^{\ 2} + k^2 U_y^{\ 2} + h^2 U_z^{\ 2}$$





U(0): actual velocity in the flow
Ueff: effective cooling velcoity (calculated from velocity calibration)
α: yaw angle (angle between velocity and wire normal)
θ: pitch angle (agle between velocity and wire wire-prong plane)
k: yaw factor
h: pitch factor
(x,y,z): probe oriented coordinate system

15.5 The Constant Temperature Anemometer.

The constant temperature anemometer is designed with the purpose of eliminating the influence of the thermal inertia of the wire in fluctuating flows, so that the frequency limit of the instrument is mainly determined by the electronic circuitry. This is achieved by supplying electrical energy to the wire at exactly the same rate as heat is lost to the surrounding fluid medium and at the same time. Since the wire temperature is thus kept constant irrespective of the flow velocity, the importance of the heat capacitance of the wire is greatly diminished.

The operation of the CTA anemometer can be explained as follows:

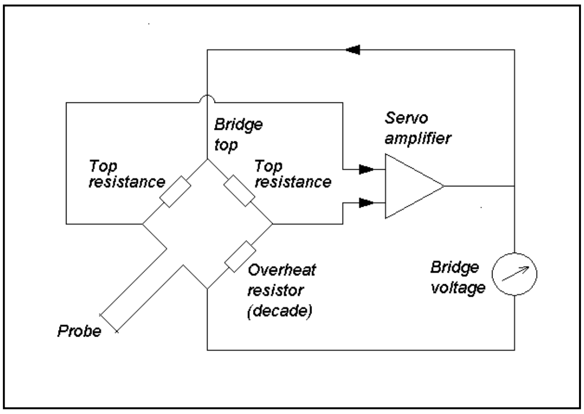
The hot-wire is placed in one arm of a Wheatstone bridge opposite a variable resistor, which defines the operating resistance, and hence the operating temperature of the hot-wire. In the case the bridge is in balance, no voltage difference exists across its diagonal. Now, if the flow velocity increases, the wire resistance will tend to decrease and an error voltage will be present at the input of the current regulating amplifier. This will cause the probe current to increase. The wire will heat and increase in resistance until the balance is restored. Because of the high gain of the current regulating amplifier, a condtion of bridge balance exists, which is practically independent of the flow velocity past the wire. The wire time constant is thus reduced by a factor of several hundred times from fractions of a milliseconds to some few microseconds. The probe current is represented by the voltage drop across the bridge. As all resitances in the bridge are constant, the squared output voltage E^2 directly represents the heat loss from the wire and can replace Q in the heat transfer equation for the wire.

CTA anemometer principle diagram:

Main components are:
Wheatstone bridge:
- Probe: *Rw*
- Overheat resistor: *R3*
- Top resistors: *R1* and *R2*

Feedback loop:
- Amplifier: *G*
- Gain shape control: *S**
- Filter: *F**
- Power amplifier: *P**
- Cable compensation: *C**

* not shown in principle diagram.

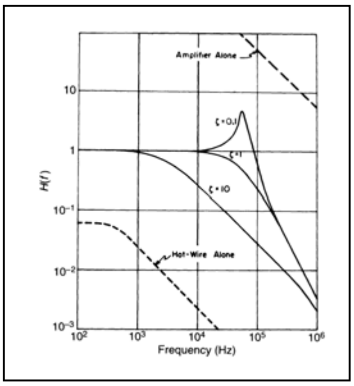


Improved wire response:

The servo-loop amplifier increases the wire frequency limit:

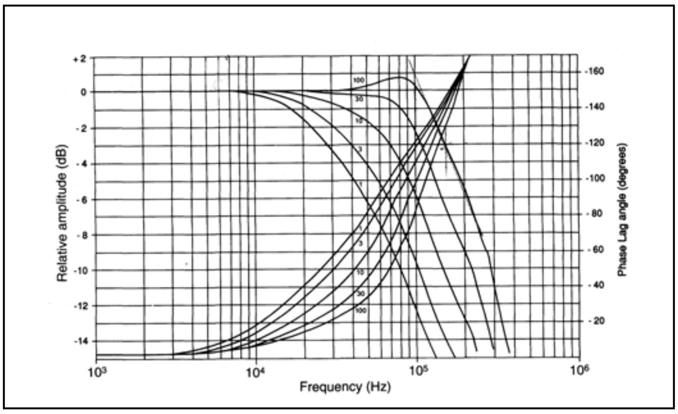
$$f_{c,CTA} = 2aSR_w f_{c,wire}$$

τ_w = wire time constant alone
a = overheat ratio
R_w = wire resistance
S = amplifier gain



Typical CTA frequency response:

Typical frequency response (amplitude damping and phase lag) of CTA with 5 μm wire probe.

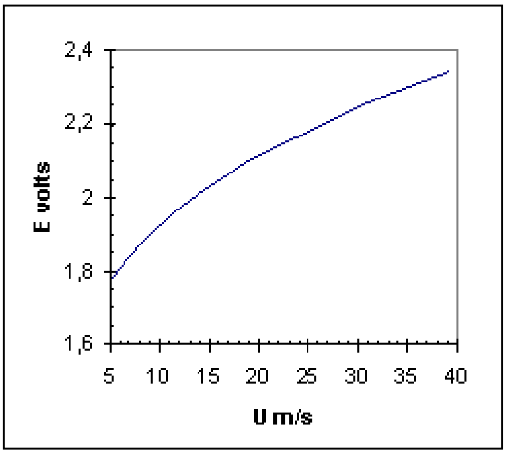


Typical velocity response:

The relation between the CTA output *E* and the velocity *U* repesents the probe calibration, from which the transfer function *U = f(E)* is derived.

$$U = \left(\frac{E^2}{B} - \frac{A(T_w - T_0)}{B} \right)^{\frac{1}{n}} \quad \text{or}$$

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



16. REFERENCES

The hot-wire anemometer literature counts more than 1200 titles covering almost all aspects of anemometry, ranging from the design of advanced electronic circuitry over sophisticated signal interpretation and data reductions to practical hints on how to mount and operate a hot-wire in a specific application. H.H. Bruun's book on Hot-Wire Anemometry from 1995 is the most comprehensive reference text book for the selection and use of hot-wire/hot-film anemometry techniques published so far. It contains an almost complete list of references up to the date of printing. Other valuable sources are DISA Information 1965-1985, which was replaced by Dantec Information 1985-1995.

The below short list of references contains some of the more important text books and papers but does not intend to be neither complete, nor fully representative. It should be regarded only as a tool, by which one can get either immidiate help or be guided to more adequate references. Copies of the listed papers are available from Dantec Dynamics on request.

Text books on Hot-wire Anemometry:

1. Bradshaw, P.: "An introduction to Turbulence and its Measurement". Pergamon Press 1971
2. Bruun, H.H.: "Hot-Wire Anemometry, Principles and Signal Analysis". Oxford Science Publications 1995.
3. Compte-Bellot, G.:"Hot-wire Anemometry." The Handbook of Fluid Dynamics edited by R.W. Johnson CRC Press LLC, 1998.
4. Fingerson, L.M.:"Thermal Anemometers." Fluid Mechanics Measurements. Edited by R.J. Goldstein. Hemisphere Publishing/Springer 1983.
5. Kovásnay, L.S.G.:" Turbulence Measurements". Physical Measurements in Gas Dynamics and Combustion. Edited by R.W.Ladenburg et al. Princeton University Press 1954.
6. Lomas, C.G.: "Fundamentals of Hot Wire Anemometry". Cambridge University Press 1986
7. Sandborn, V.A.:"Resistance Temperature Transducers". Metrology Press 1972.

Papers on Hot-wire Anemometry in general:

8. Baldwin, L.V. et al.:"Heat Transfer From Transvers and Yawed Cylinders in Continuum, Slip, and Free Molecule Air Flows." Journal of Heat Transfer, May 1960.
9. Bradshaw, P.:"Thermal methods of flow measurement." J. Phys. E.: Sci. Instrum. 1968 Series 2 Volume 1.
10. Freymuth, P.:"Frequency response and electronic testing for constant-temperature hot-wire anemometers." Journal of Physics E.: Scientific Instruments 1977 Volume 10, 705-710.
11. Freymuth, P.:"Calculations of square wave test for frequency optimised hot-film anemometers." Journal of Physics E.: Scientific Instruments 1981 Volume 14, 238-240.
12. Freymuth, P.:"Interpretations in the control theory of thermal anemometers." Meas. Sci. Technol. 8 (1997) 174-177.
13. Freymuth, P.:"Second or third order control theory for constant-temperature hot-wire anemometers." Experiments in Fluids 23 (1997) 175-170.
14. Jørgensen, F.E.:"The computer-controlled constant-temperature anemometer. Aspects of set-up, probe calibration, data acquisition and data conversion." Meas. Sci. Technol. 7 (1996) 1378-1387.
15. King, L.V.:"On the convection of heat from small cylinders in a stream of fluid: Determination of the convectiomn constants of small platinum wires with applications to hot-wire anemometry." Phil. Trans. Roy. Soc. A214 (1914), 373-432

16. Weiss, J. et al.:"Method for the determination of frequency response and signal to noise ratio for constant-temperature hot-wire anemometers". Review of Scientific Instruments, Volume 72, Number 3, March 2001.

Papers on Probes and probe response:

17. Bellhouse, B.J. et al.:"Low-Frequency Characteristics of Hot-Film Anemometers." DISA Information No. 6. 1968.
18. Bergström, H. et al.:"Calibration of a Three-Axial Fiber-Film System for Meteoroligical Turbulence Measurements." Dantec Information No. 5, 1987.
19. Bonis, M. et al.:"A Heat Transfer Law for a Conical Hot-film Probe in Water." DISA Information No. 14, 1973.
20. Bremhorst, K.. et al.:"Response of hot-wire anemometer probes to a stream of air bubbles in a water flow." J. Phys. E.: Sci. Instrum. Volume 9, 1976.
21. Chew, Y.T. et al.:"The directional sensitivities of crossed and triple hot-wire probes." J. Phys. E.: Sci. Instrum. 21 (1988) 613-620.
22. Christman, P.C. et al.:"Hot-wire anemometer behaviour in low velocity air flow." J. Phys. E.: Sci. Instrum. 1976 Volume 14, 1981.
23. Collis, D.C. et al.:"Two-dimensional convection from heated wires at low Reynolds numbers." J. Fluid Mech., 6, (1959), 357-384.
24. Friehe, C.A. et al.:"Deviations From the Cosine Law for Yawed Cylindrical Anemometer Sensors." Journal of Applied Mechanics, Transactions of the ASME 68-WA/APM-16.
25. Geremia, J.O.:"Experiments on the Calibration of Flush Mounted Film Sensors." DISA
26. Gieseke, T.J.:"An experimental approach to the calibration and use of triple hot-wire probes." Experiments in Fluids 14, 305-315 (1993).
27. Hollash, K. et al.:"Calibration of Constant-Temperature Hot-Wire Anemometers at Low Velocities in Water with Variable Fluid Temperature." Journal of Heat Transfer, ASME Paper No. 71-HT-9.
28. Johnson, F.D. et al.:"A variable angle method of calibration for X-probes applied to wall-bounded shear flow." Experiments in Fluids 2, 121-130 (1984).
29. Jørgensen, F.E.:"Directional Sensitivity of Wire and Fibre-Film Probes." DISA Information No. 11. 1971.
30. Kassab. S.Z.:"Effect of the hot-wire length on the determination of the length scale of large eddies." Meas. Sci. Technol. 2 (1991) 647-652.
31. Ligrani, P.M. et al.:"Subminiature hot-wire sensors: development and use." J. Phys. E.: Sci. Instrum. 20 (1987).
32. Marasli, B.:"A calibration technique for multiple-sensor hot-wire probes and its application to vorticity measurements in the wake of a cylinder." Experiments in Fluids 15, 209-218 (1993).
33. Norman, B. :"Hot-wire Anemometer Calibration at High Subsonic Speeds." DISA Information No. 5. 1967.
34. Perry, A.E. et al.:"Vibration of hot-wire anemometer filaments." J. Fluid Mech. (1967), vol. 50, part 4, pp. 815-825.
35. Schewe, J. et al.:"Error-tolerant calibration of dual sensor probes used in turbulent wall boundary layer." Experiments in Fluids 9, 285-289 (1990).
36. Strohl, A. et al.:"Aerodynamic Effects Due to Configuration of X-Wire Anemometers." Journal of Applied Mechanics, Transactions of the ASME 73-APM-P.
37. Sumer, B.M. et al.:"Two-component hot-film probe for measurement of wall shear stress." Experiments in Fluids 15, 380-384 (1993).
38. Tagawa, M. et al.:"Evaluation of X-probe response to wire separation for wall turbulence measurements." Experiments in Fluids 12, 413-421 (1992).
39. Teo, C.J. et al.:"The dynamic response of a hot-wire anemometer: IV. Sine wave voltage pertubation testing for near-wall hot-wire/film probes and the presence of low-frequency response characterisics." Meas. Sci. Technol. 12 (2001) 37-51.

40. Turan, Ö.F. et al.:”Effect of structural vibrations on hot-wire probe response.” Widell, K.E.:”Stresses and Deformations in Hot-Wire Probes.” DISA Informatioon No. 2, 1965
41. Yeung, C.P. et al.:”Numerical calibration and verification tests of othogonal triple-hot-wire probe.” Meas. Sci. Technol. 4 (1993) 1446-1456.
42. Zank, I.:”Sources of Errors and Running Calibration of Three-Dimensional Hot-Film Anemometers Especially near the Sea Surface.” DISA Information No. 26. 1981.

Papers on methods and applications:

43. Abdel-Rahmann, A.A.:”An X-array hot-wire technique for heated turbulent flows of low velocity.” J. Phys. E.: Sci. Instrum. 22 (1989) 638-644.
44. Brown, G.L. et al.:”A Small, Fast-Response Probe to Measure Gas Composition of Binary Gas Mixtures.” AIAA Journal, Vol. 10, No. 5, 1972, 649-652.
45. Bruun, H.H.et al:”Velocity component measurements by X hot-wire anemometry.” Meas. Sci. Technol. 1 (1990) 1314-1321.
46. Butterfield, R.G.:”Application of thermal anemometry and high-frequency measurement of mass flux to aeolian sediment transport.” Geomorphology 29 (1999) 31-58.
47. Chew, Y.T. et al.:”A critical evaluation of the explicit data analysis algorithm for a crossed wire anemometer in highly isotropic flow.” Meas. Sci. Technol. 1 (1990) 775-781.
48. Demin, V.S.:”Interpretation of Hot-Wire Anemometer Readings in a Flow with Velocity, Pressure and Temperature Fluctuations.” Fluid Mechanics- Soviet Research, Vol. 2, No. 3, May-June 1973.
49. Frota, M.N.:”Analysis of the Uncertainties in velocity Measurements and Technique for Turbulence Measurements in Complex Heated Flows with Multiple Hot Wires”. Stanford University 1982.
50. Gaullier, C.:”Measurement of Air Velocity by Means of a Triple Hot-Wire Probe.” DISA Information No. 21. 1977.
51. Hoffmeister, M.:”Using a Single Hot-Wire Probe in Three-Dimensional Turbulent Flow Fields.” DISA Information No. 13. 1972.
52. Kelso, R.M. et al.:”A novel flying hot-wire system.” Experiments in Fluids 16, 181-18684 (1994).
53. Khoo, B.C. et al.:”On near-wall hot-wire measurements.” Experiments in Fluids 29, 448-460 (2000).
54. Löfdahl, L.:”Hot-Wire Techniques for the Determination of the Reynolds Stress Tensor in Three-Dimensional Flows”. Dantec Information No. 35, 1986.
55. Smiths, A.J. et al.:”Constant Temperature Hot-Wire Anemometer Practice in Supersonic Flows, Part 1: The Normal Wire:” Experiments in Fluids 1, 83-92 (1983).
56. Thompson, B.E.:”Appraisal of a Flying Hot-wire Anemometer”. Dantec Information No. 4, 1987.
57. Van Dijk, A.:”Aliasing in one-point turbulence measurements.” Dissertation, Technical University Delft 1999.
58. Wark, C.E. et al.:”A rotating hot-wire technique for spatial sampling of disturbed and manipulated duct flows.” Experiments in Fluids 9, 191-196 (1990).
59. Wyngaard, J.C.:”Measurement of small-scale turbulence structure with hot-wires.” J. Phys. E.: Sci. Instrum. Series 2 Volume 1, 1968.

Papers on disturbing effects:

60. Bearman, P.W.:”Corrections for the Effect of Ambient temperature Drift on Hot-Wire Measurements in Incompressible Flows.” DISA Information No. 11. 1971.
61. Durst, F. et al.:”Influence of humidity on hot-wire instruments”. Meas. Sci. Technol. 7 (1996) 1517-1528.
62. Hebbar, K.S.:”Wall Proximity Corrections for Hot-Wire Readings in Turbulent Flows.” DISA Information No. 25. 1980.

63. Löfdahl, L. et al.:"The influence of temperature on the measurements of Reynolds stresses in shear free turbulence near a wall." Experiments in Fluids 25, 160-164 (1998).
64. Martinez- Val, R. et al.:"Sensor contamination Effects in Hot-Wire Anemometry in Air." DISA Information No. 27. 1982.
65. Mojola, O.O.:"The Effects of Orientation of a Hot-Wire Probe Body in Turbulent Shear Flow." DISA Information No. 23. 1978.
66. Firasat Ali, S.:"Hot-wire anemometry in moderately heated flow." Rev. Sci. Instrum., Vol. 46, No. 2, 1975.
67. Bremhorst, K.:"Effect of fluid temperature on hot-wire anemometers and an improved method of temperature compensation and linearisation without use of small signal sensitivities." J. Phys. E.: Sci. Instrum. Vol. 18, 1985.
68. Schubauer, G.B.:"Effect of humidity in hot-wire anemometry." National Bureau of Standards, Research Paper RP850, 1935.