NORDITA-FLOW Spring School on Turbulent Boundary Layers – 6-9 April 2010

Issues in Experiments

Material prepared
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iTi 2010

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Deadline: April 16th

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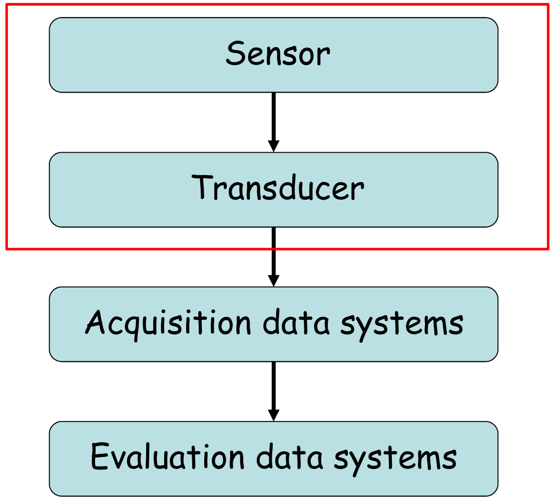
Outline

- The measurement chain
- Sensors and transducers for turbulence measurements
  - Pressure measurements
  - Thermal measurements
  - Optical measurements
- WSS measurements
- The facilities

Literature

- **Springer Handbook of Experimental Fluid Mechanics**, Cameron Tropea, Alexander L. Yarin, John F. Foss (2007), **ISBN-10:** 3540251413
- **Measurement in Fluid Mechanics** Stavros Tavoularis, Cambridge University Press (2009) **ISBN-10:** 0521138396
- **Fluid Mechanics Measurements**, R. Goldstein, CRC Press; (1996) **ISBN-10:** 156032306X
- **Low-Speed Wind Tunnel Testing**, Jewel B. Barlow , William H. Rae, Alan Pope, Wiley-Interscience; (1999) **ISBN-10:** 0471557749

Measurement chain

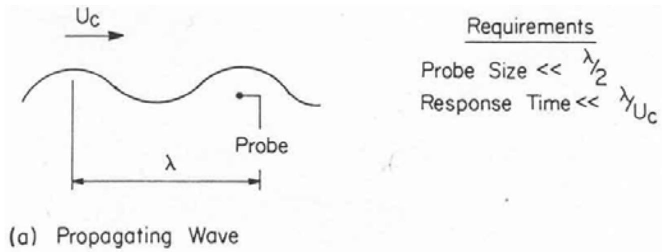


High Reynolds turbulent wall bounded flows

- Presence of the wall
- Large velocity gradients
- Time and length scales
- A full appraisal in not possible (errors can be accurately estimated only at small Re)

Sensors' characteristics

- Spatial and temporal resolution



- To keep a good temporal resolution it is better to keep the velocity low and increase the Reynolds number with a different mean than velocity

Sensors' characteristics

- Spatial and temporal resolution
  - In general turbulent flows size and frequency of the smallest dynamical motion are related to the Kolmogorov length scale

$$\eta = \left(\nu^3/\varepsilon\right)^{1/4} \qquad f = \left(U/2\pi\eta\right)$$

  - In wall bounded flows is the inner length scale

$$\ell = \left(\nu/u_\tau\right) \qquad f = \left(u_\tau^2/\nu\right)$$

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Real sensors' characteristics

- Spatial and temporal resolution
  - Must be specified for both
- Other problems
  - Accuracy (calibration, …)
  - Blockage (flow interference,..)
  - Robustness (vibration, fragility,..)
  - Wall interference (conduction, reflection, ..)
  - Seeding
  - Sensitive to velocity gradient
  - Access to the measurement region
  - Cost

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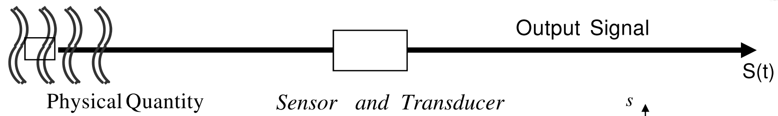
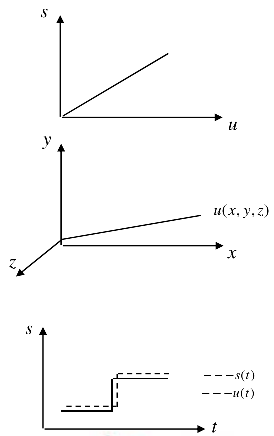
Ideal sensor/transducer



- Output signal is proportional to the magnitude of the physical quantity
- The physical quantity is measured at a point in space
- The output signal represents the input without frequency distortion
- Low noise on output signal
- Sensor does not interfere with the physical process
- Output is not influenced by other variables



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Physical interesting quantities

- Velocity
- Wall shear stress
- Vorticity
- Fluctuating pressure
- Distance from the wall

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Velocity

- Pressure probes
- Hot-wire anemometry
- Optical system (LDV)

Pressure based velocity mesurements

- Steady flow, low velocity, viscosity negligible: Bernoulli's law holds

$$p_{tot} = p_s + \frac{1}{2}\rho V^2$$

- High velocity:

$$p_{tot} = p_s + \frac{1}{2}\rho V^2 (1+\varepsilon_p)$$

Corrective term f(M)

$$V = \sqrt{\frac{2(p_{tot} - p_{st})}{\rho(1+\varepsilon_p)}}$$

Pressure based probes

Chue PAS (1975)
McKeon and Smits MST (2002)
McKeon, Li, Jiang, Morrison and Smits MST (2003)
Experimental Fluid Mechanics SPRINGER HANDBOOK

Velocity measurements - compressibility effects

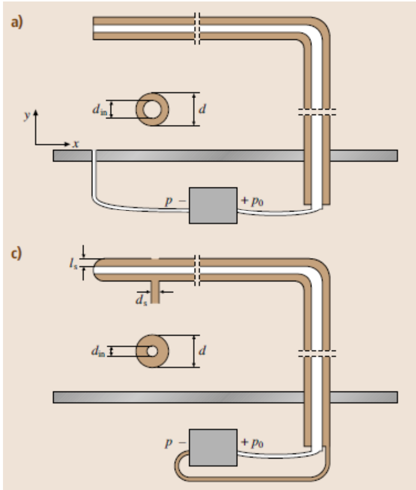
$$p_0 - p = \frac{\rho U^2}{2}\underbrace{(1 + \frac{M^2}{4} + \frac{2-\gamma}{24}M^4 + \ldots\ldots)}_{\varepsilon_p}$$

M	ε_p
0	0
0.1	0.0025
0.2	0.010
0.3	0.023
0.5	0.083
1.0	0.274

Note that the error in velocity is about half of ε_p !

Measurement techniques

- They strictly depend on the flow under consideration:
  - Wall bounded flows (pitot + wall tapping)
  - Free flows (Prandtl)



From Experimental Fluid Mechanics SPRINGER HANDBOOK

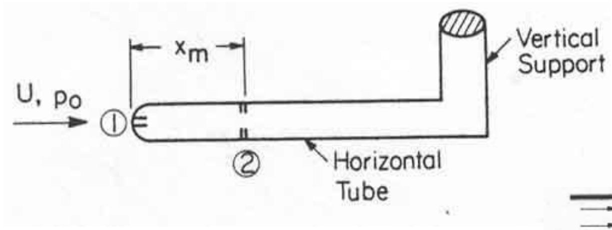
Static probes

- The probe must be aligned with the flow (this effect can be reduced by using several holes)
- Since the pressure is measured with holes, then the same problems of the wall tappings must be considered
  - Effects of tip shape (geometry depends from flow regime)
  - Effects of probe blockage
  - Effects of hole position
  - Effects of the support

Static pressure probe – Basic principles

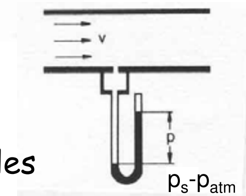
STATIC PROBES

Presence of holes at a distance of 3D from the leading edge and 8-10D from the stem.

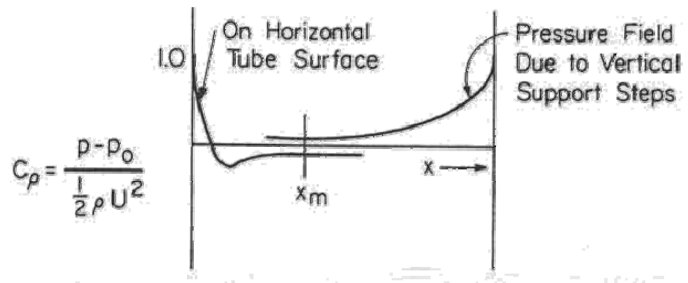


WALL TAPPING

the static pressure is measured using holes in the surface



Blockage effect



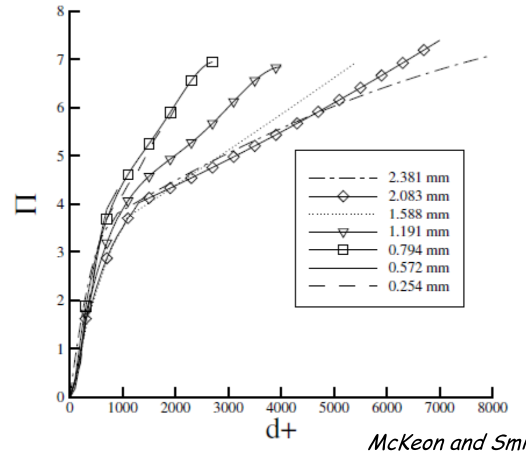
$$C_p = \frac{p - p_0}{\frac{1}{2}\rho U^2}$$

- Nose acceleration and probe support effects may compensate

Wall tappings

- The flow is very complex in proximity of the tapping (only low Re simulations)
  - Effects of orifice shape
  - Effects of orifice orientation
  - Effects of surface orientation
  - Shape and position of the cavity (minimum depth)
  - Compressibility
  - Effects of the tapping orifice condition
  - Effect of the distance from the measured point

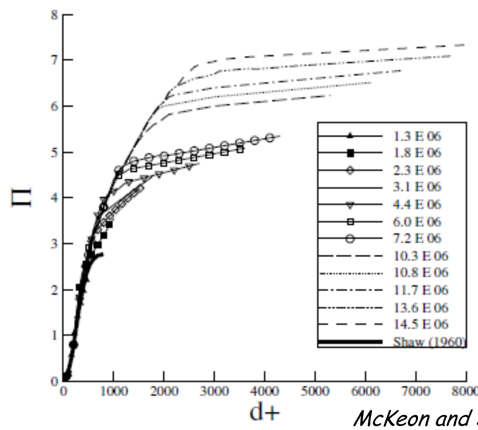
Effect of d+



McKeon and Smits MST (2002)

- Less influence when d increases

Effect of d+



McKeon and Smits MST (2002)

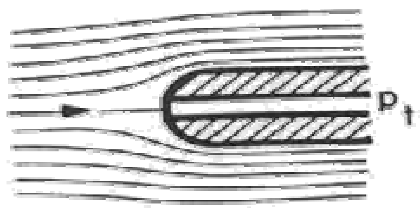
- More problematic for high Re

Total pressure probe

The stagnation pressure is obtained when the fluid is brought to rest through an isentropic and adiabatic process.

In subsonic flow the Pitot tube measures the stagnation pressure

(French hydraulic engineer 1695-1771)



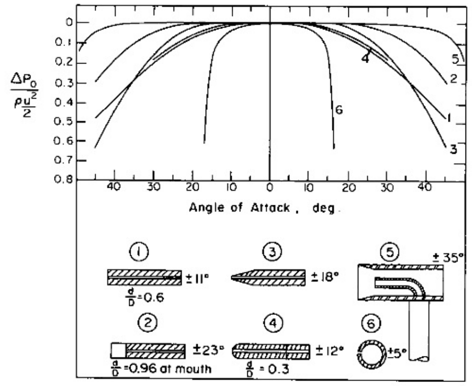
Total pressure

$$C_p = \frac{p_{0m} - p}{\frac{1}{2}\rho U^2} = f(\vartheta, \mathrm{Re}_d, M, \frac{\overline{u'^2}}{U^2}, \frac{\overline{v'^2}}{U^2}, \frac{\overline{w'^2}}{U^2}, \alpha, \frac{y}{d})$$

- Incoming flow direction
- Local Reynolds number (viscosity)
- Mach number
- Velocity gradient
- Wall proximity
- Turbulence

Total pressure probe – direction sensitivity

Less sensitivity to the inclination of the flow in respect to the longitudinal axis than the static pressure probe.



From Chue

FIG. 15. Yaw characteristics for various pitot-head shapes.

Total pressure probe

- Effects of finite dimensions
  - Pressure measured in a finite region (not a single streamline) -> spatial averaging
  - This effect can be limited with small probes (be carefull : robustness, time response)
  - Blockage (d/L)
- Directional sensitivity

Total pressure probe

- Effects of the ratio between the inner to the outer diameter of the Pitot tube (the sensitivity grows when this ratio fall).
  - Particular head's shape allows measures independence until an angle of inclination of 35°.

Total pressure probe

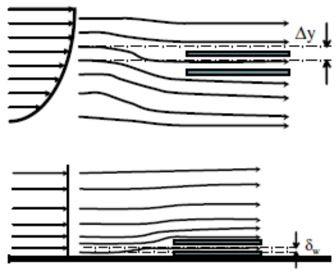
- Effects of viscosity (in high Reynolds number measurement Red can be low due to the small dimensions of the probe)
- Viscous effect are negligible for $Re_D>100$
- For $Re_D>30$

$$C_p = 1 + \frac{10}{Re_d^{1.5}}$$

Total pressure – velocity gradient

1) Velocity gradient interference

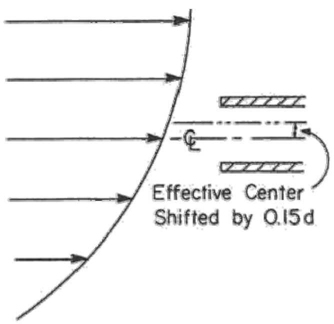
2) With the presence of a flat wall parallel to the probe axis there could be a reflection effect with the consequent measured pressure higher than the total pressure. This effect is negligible for y>2d from the wall.



McKeon, Li, Jiang, Morrison and Smits MST (2003)

Total pressure – velocity gradient

1) Indicated Pitot pressure > total pressure of the undisturbed flow if a Pitot tube is operated in a region where the total pressure varies in a direction ortoghonal to the asymptotic flow (e.g Boundary layer).



Total pressure – velocity gradient

- Error 1) is normally corrected by changing the probe position rather than correcting the flow velocity

$$\frac{\Delta y}{d} = \varepsilon, \quad \varepsilon = 0.15 \quad (MacMillan)$$

$$\frac{\Delta y}{d} = 0.18\alpha(1-0.17\alpha^2), \quad \alpha = \frac{d}{2U(y_c)} \left.\frac{dU}{dy}\right|_c \quad (Zagarola)$$

$$\frac{\Delta y}{d} = 0.15\tanh(4\sqrt{\alpha}), \quad (McKeon)$$

- This is based on analytical displacement correction for a sphere in a velocity gradient

Total pressure – velocity gradient

- Wall correction

$$\frac{\Delta U}{U} = 0.015\exp\left[-3.5\left(\frac{y}{d} - 0.5\right)\right] \quad (MacMillan)$$

- A new correction is proposed based on Preston probe pressure data

$$\frac{\delta_w}{d} = \begin{cases} 0.150 & for \quad d^+ < 8 \\ 0.120 & for \quad 8 < d^+ < 110 \\ 0.085 & for \quad 110 < d^+ < 1600 \end{cases}$$

Measurement errors due to turbulence

A physical time-dependent quantity can generally be splitted in a mean part and in a fluctuating part

$$v(t) = V + v'(t) \qquad p(t) = P + p'(t)$$

From Bernoulli's law:

$$P_{tot} + p'_{tot} = P_{st} + p'_{st} + \frac{1}{2}\rho\left(V^2 + 2Vv' + v'^2\right)$$

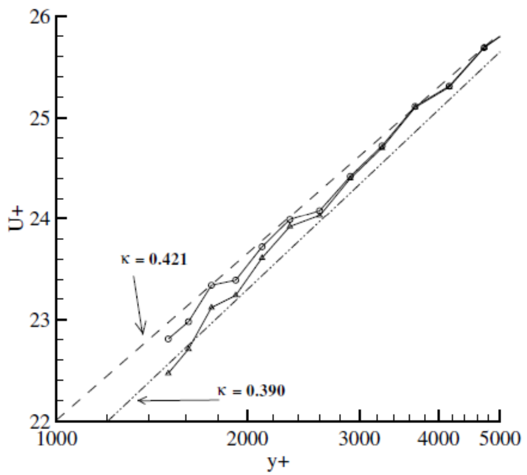
Taking the time-average:

$$P_{tot} = P_{st} + \frac{1}{2}\rho\left(V^2 + \overline{v'^2}\right)$$

Error due to fluctuating velocity

Effect of the anisotropy

How important wall correction are ?



McKeon, Li, Jiang, Morrison and Smits MST (2003)

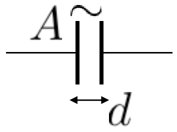
Measurement errors due to turbulence

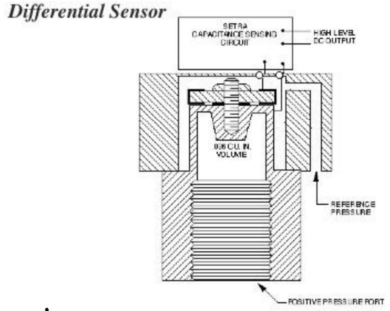
Another effect is linked to the radial gradient of the static pressure due to the fluctuations

This is of the opposite sign than the turbulence one. Therefore they compensate.

Differential Pressure transducers

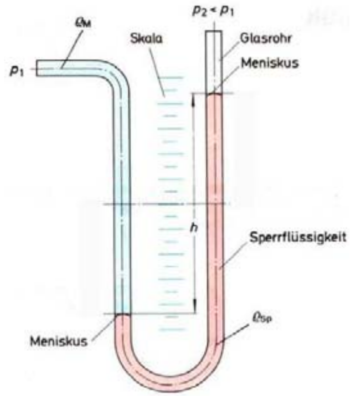
Capacitance principle $C \sim \frac{A}{d}$

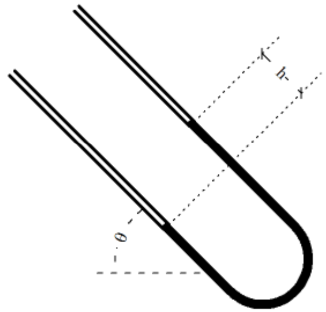




- Very accurate
- Need to be calibrated (time to time)
- Expensive for multi point measurements

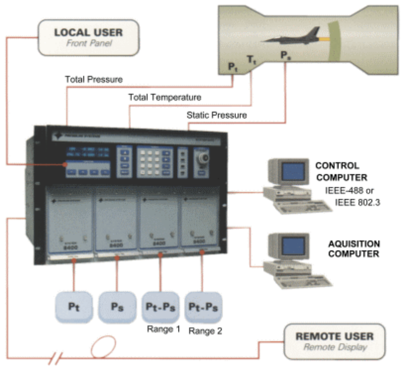
Pressure transducers





$p_d = \rho\ h \sin(\theta)$

Pressure Scanners



Pressure transducers

Betz manometer

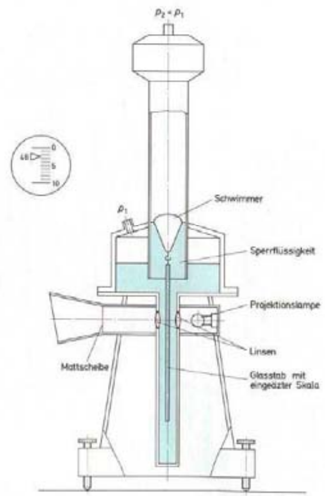
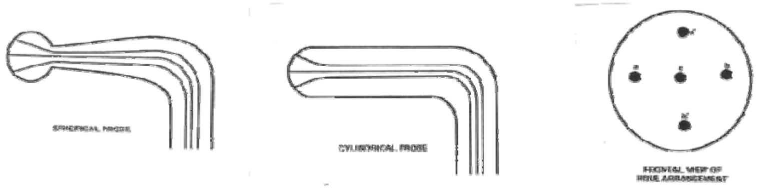


Abbildung 4 Betz Präzisionsmanometer

Multi component velocity measurements

- Five hole Pitot



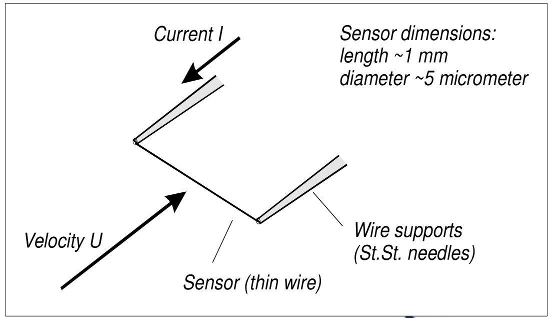
- Pressure distributions on the probe's head is function of its geometry and of the flow direction
- By sampling this distribution in five points is possible to determine the direction and magnitude of the velocity vector
- Very large gradient sensitivity

Principles of hot wire operation

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

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

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



Thermal anemometry (Hot wires)

Ligrani and Bradshaw EXF (1987)
Li, McKeon, Jiang, Morrison and Smits MST (2004)
Hutchins, Nickels, Marusic and Chong JFM (2009)
Zanoun, Durst and Shi IJHMT (2009)
Orlu and Alfredsson EXF (2010)
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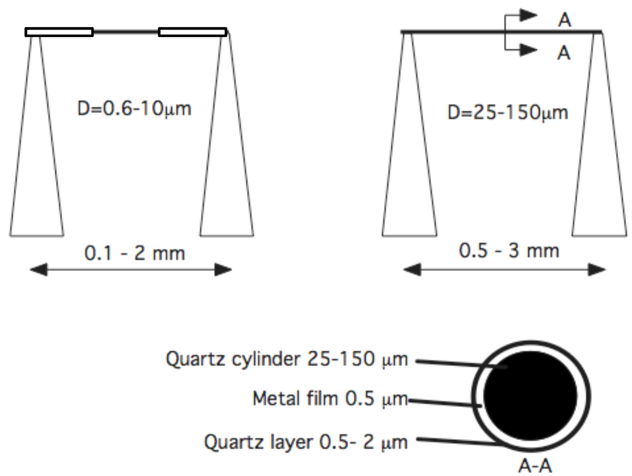
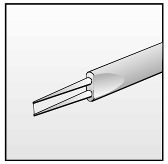
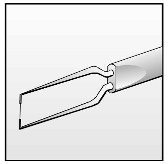
Sensors: hot wire and hot film probes



Commercial Probe types

- Miniature Wire Probes
  Platinum-plated tungsten,
  5 μm diameter, 1.2 mm length
- Gold-Plated Probes
  3 mm total wire length,
  1.25 mm active sensor
  copper ends, gold-plated





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

Standard wire material suitable for hot-wires

Tungsten wire (W, also called Wolfram)

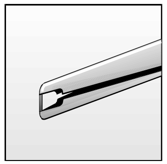
- high strength
- can be used at high temperatures
- need to be welded
- diameters down to 5μm available

Platinum (Pt) and Platinum/Rhodium (Pt/Rh) wires

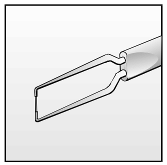
- produced down to 0.6μm through Wollaston process
- can be soldered

Commercial Probe types

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

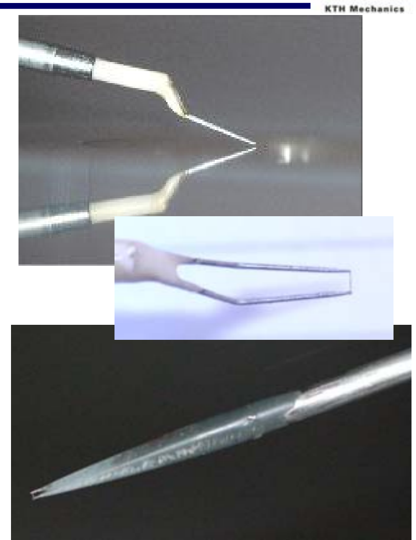


- Fiber-Film Probes
  "Hybrid" - film deposited on a thin wire-like quartz rod (fiber)



Home made probes

- Boundary Layer types
- Straight Type
- Wires *(pure Pt/silver coated)*:
  - Stubbed = Partially Etched
  - Stubless = Fully Etched wires



Governing equation

- Governing Equation: $\frac{dE}{dt} = W - H$

E = thermal energy stored in wire

$E = C_W T_S$

C_W = heat capacity of wire

W = power generated by Joule heating

$W = I^2 R_W$

recall $R_W = R_W(T_W)$

H = heat transferred to surroundings

Simplified static analysis

$$W = H \Rightarrow I^2 R_W = q \cdot A \cdot \Rightarrow I^2 R_W = \frac{Nu \cdot k_f}{d} \cdot A \cdot (T_W - T_a)$$

q = heat transfer/unit area = $h(T_w - T_a)$
A = heat transfer area
d = wire diameter
k_f = heat conductivity of fluid
Nu = Nusselt number = hd/k

Forced convection regime ($Re \gg Gr^{1/3}$)

$Nu = A_1 + B_1 Re^n$

$E = A_2 + B_2 U^n$ "King's law"

Simplified static analysis

- For equilibrium conditions the heat storage is zero:

$$\frac{dE}{dt} = 0 \quad \Rightarrow \quad W = H$$

and the Joule heating W equals the convective heat transfer H

- Assumptions

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

Temperature effects

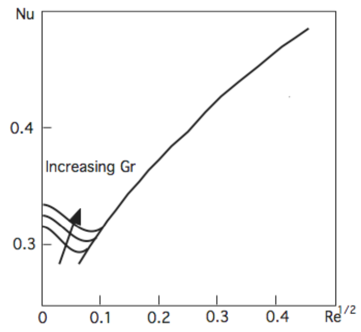
- A and B depend on wire diameter and flow temperature

$$\frac{dA}{A} = 0.886 \frac{dT_a}{T_a} \qquad \frac{dB}{B} = 0.006 \frac{dT_a}{T_a}$$

- Temperature correction or temperature control (better !)

Nu vs Re, influence of Gr

$Gr = gd^3\beta\Delta T/\nu^2$



To avoid buoyancy effects Re > Gr 1/3
In air at standard case: U > 0.07 m/s

$$U_{eff} = k_1(E^2 - E_0^2)^{1/n} + k_2(E - E_0)^{1/2}$$

Alfredsson and Johansson (???)

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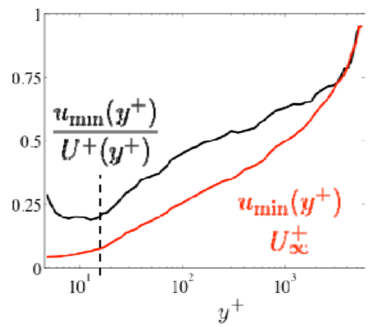
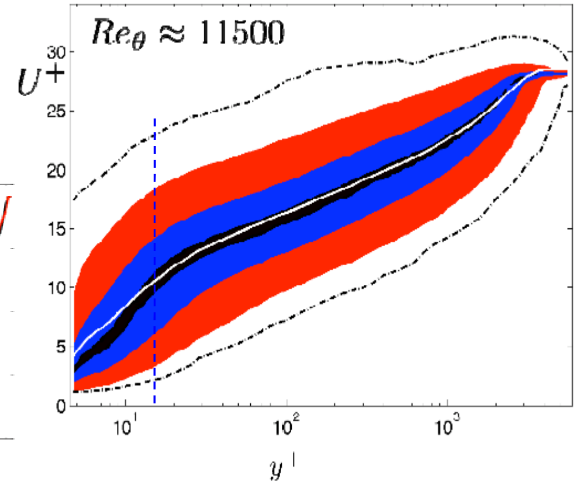
Demands on the calibration

Firm calibration down to
- 1/5th of $U^+(y^+ = 15)$
- 1/12th of U_∞^+





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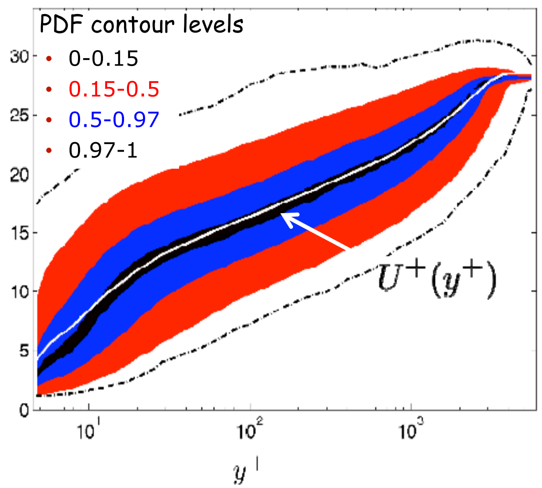
PDF and lowest occurring velocity fluctuations

$Re_\theta \approx 11500$



Orlu and Alfredsson EXF (2010)

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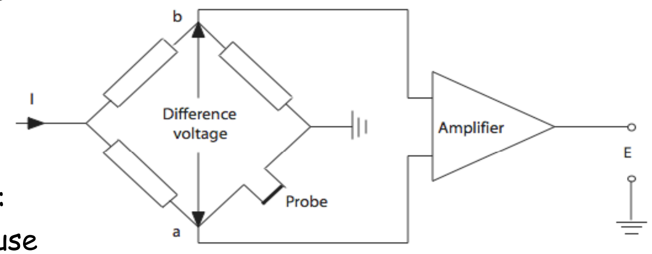
Constant current anemometer CCA

- Principle:
  Current through sensor is kept constant
- Advantages:
  - Low noise
- Disadvantages:
  - Difficult to use
  - Output decreases with velocity
  - Risk of probe burnout
  - low frequency response (a filter's response is tuned to compensate the thermal lag of the sensor)



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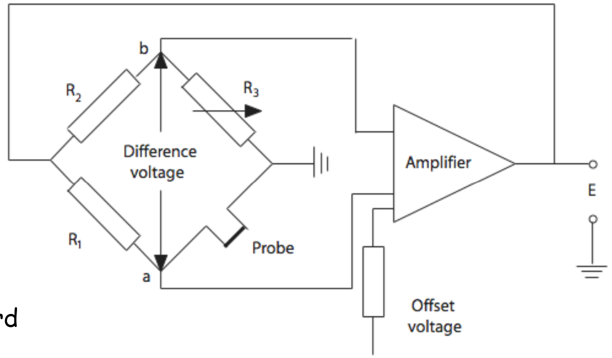
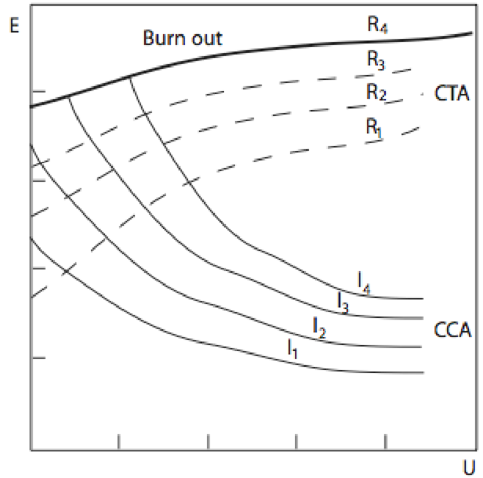
Constant Temperature Anemometer CTA

- Principle:
  Sensor resistance is kept constant by servo amplifier
- Advantages:
  - Easy to use
  - High frequency response
  - Accepted standard
- Disadvantages:
  - More complex circuit
  - "high" noise

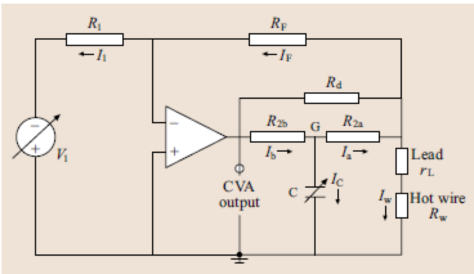


Output fron CCA and CTA



Constant Voltage Anemometer CVA

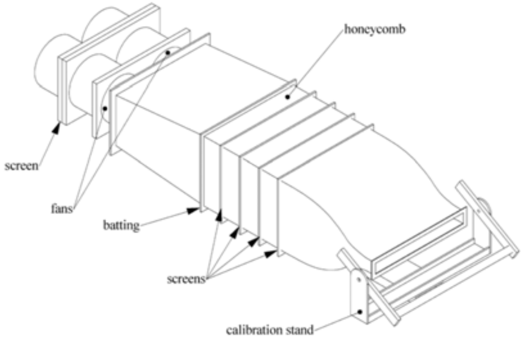
- Principle:
  Voltage through sensor is kept constant
- Advantage
  - Large response
  - High frequency response
  - Stable
  - Cable independent
- the thermal lag is partially compensated during measurements and is fully compensated when postprocessing the data



Calibration

- Dynamic
- Static
  - "in situ" (free stream, potential core,..)
  - Ad hoc apparatus

Ad hoc apparatus

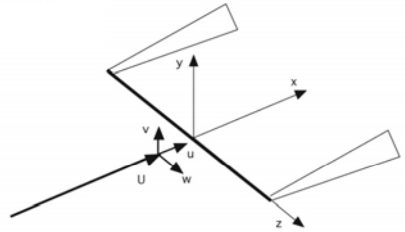


Alessandro Talamelli

Hot wire response in turbulent boundary layer

$$U_{eff}^2 = (U+u)^2 + h^2 v^2 + k^2 w^2$$

$|u|, |v|, |w| << U$



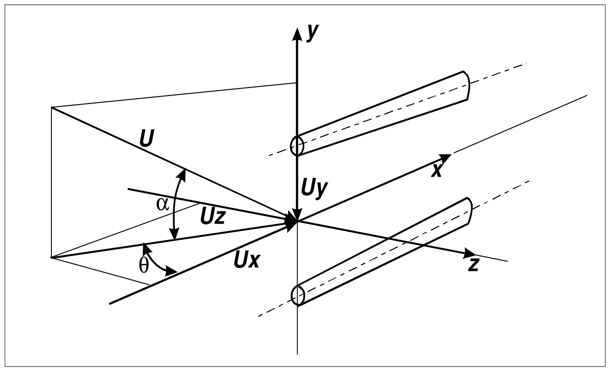
$$U_{eff} = U\Big\{1 + \frac{u}{U} + \frac{1}{2}\Big[h^2(\frac{v}{U})^2 + k^2(\frac{w}{U})^2\Big] - \frac{1}{2}\frac{u}{U}\Big[h^2(\frac{v}{U})^2 + k^2(\frac{w}{U})^2\Big] + O(\frac{u}{U})^4\Big\}$$

$$U_{eff} = U + u$$

Alessandro Talamelli

Directional response

Probe coordinate system



Velocity vector U is decomposed into normal U_x, tangential U_y and binormal U_z components.

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Sensor (spatial resolution)

- Sometimes wire diameter can be 20% larger than what is declared
- In wall bounded flow of course the diameter is kept as small as possible
- What about l/d ?
  - Heat conduction problems
  - Flow interference problems (Analytical developments are not possible, Computer simulations needed)

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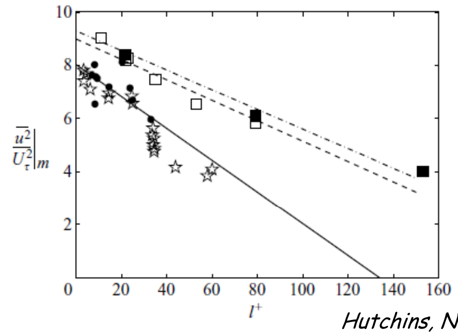
How small l/d can be ?

- Several works in the literature suggest l/d > 200 to avoid conduction losses
- l+ less then 20 to avoid spatial averaging
- Skewness and flatness not influenced

Ligrani and Bradshaw EXF (1987)

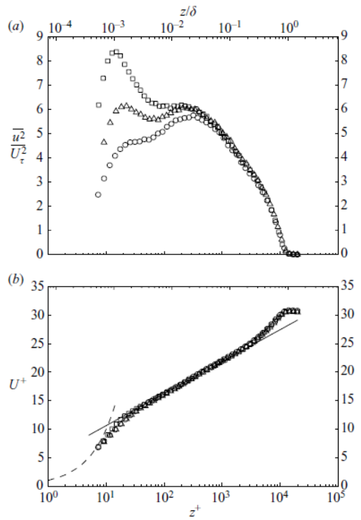
Near wall peak



Hutchins, Nickels, Marusic and Chong JFM (2009)

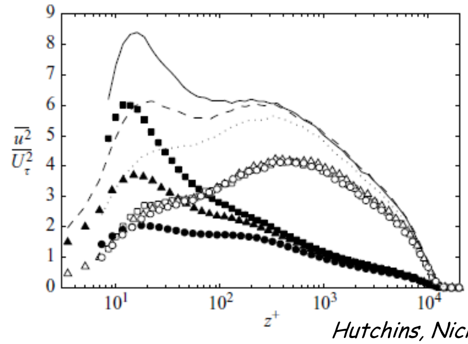
- l+=20 might not be enough
- The difference from ideal wire response decreases with Re

Near wall peak



Hutchins, Nickels, Marusic and Chong JFM (2009)

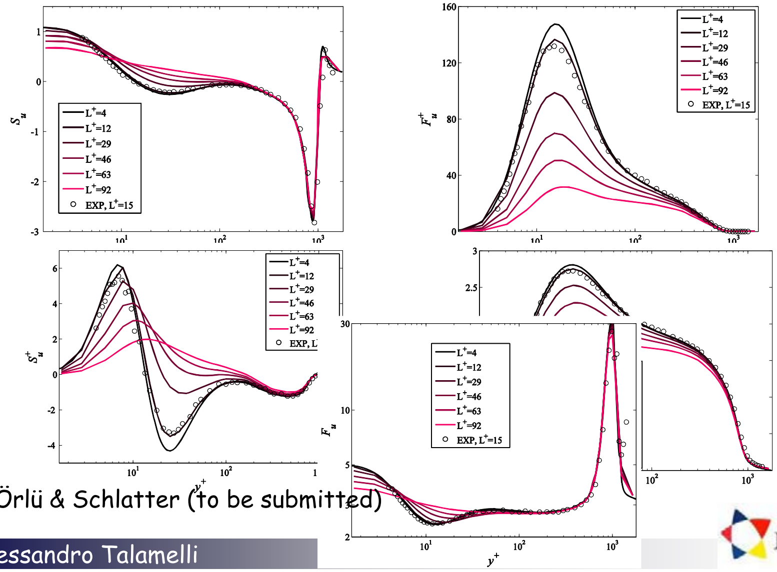
Large and small scales contr.



Hutchins, Nickels, Marusic and Chong JFM (2009)

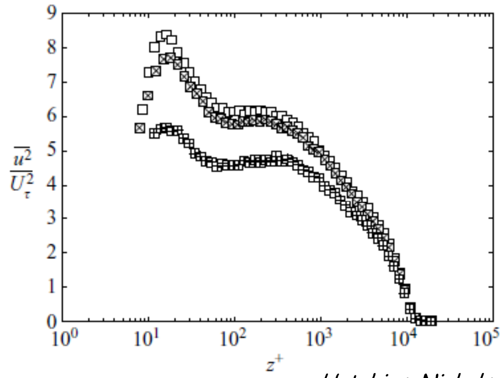
- Large scales do not contribute to the peak intensity decrease with l+

Effects of l+ on PDF



Örlü & Schlatter (to be submitted)

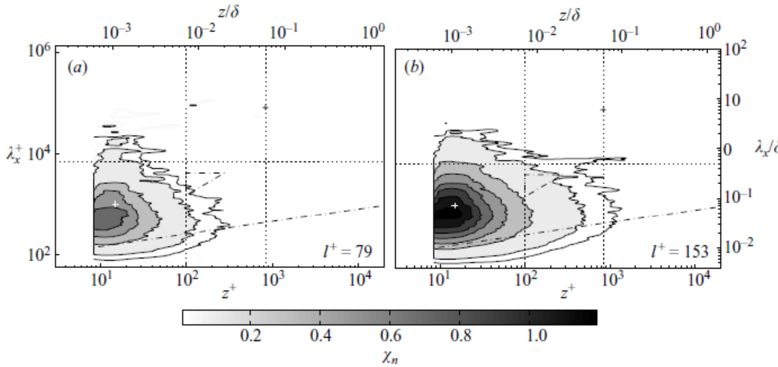
Effects of l/d on fluctuations



Hutchins, Nickels, Marusic and Chong JFM (2009)

- For same l+

Effects of l+ on spectra

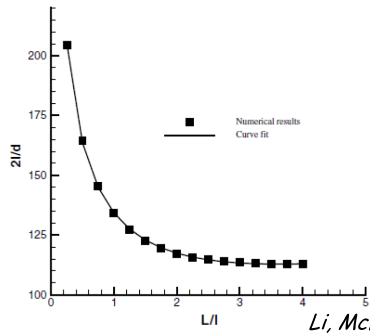


Hutchins, Nickels, Marusic and Chong JFM (2009)

- Effect on spectra spread inside the bl

Conduction losses (effect of stubs)

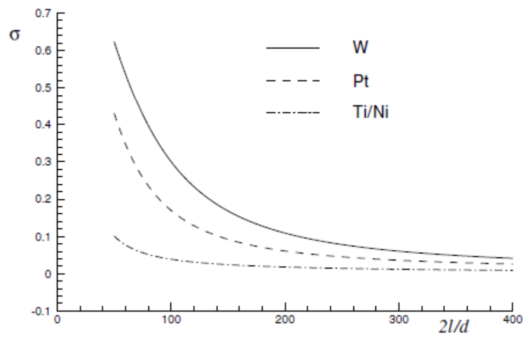
- By means of a specific heat transfer analysis of the hot wire it is possible to assess the temperature distribution for different geometries
- Effect of stubs can be analyzed (Pt wire, Rew=10, accetable end-cooling effect)



Li, McKeon, Jiang, Morrison and Smits MST (2004)

Spatial resolution

- Effects of different hot-wire materials (acceptable end-conduction effect)



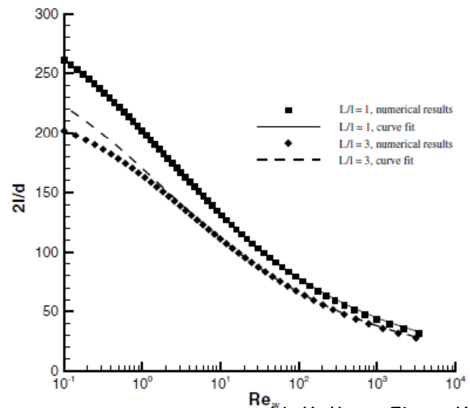
Li, McKeon, Jiang, Morrison and Smits MST (2004)

Effect of wire length l/d

- Decrease of turbulence peak near the wall (at l/d equal 100 there is an attenuation of approx 20%)
- These effects extend far beyond the inner layer
- l/d smaller for larger wire reynolds number
- The use of new material can reduce the effect of l/d. For instance Ti/Ni shows an ecellent behavior

Spatial resolution (Li)

- Effects of Reynolds number (acceptable end-conduction effect)

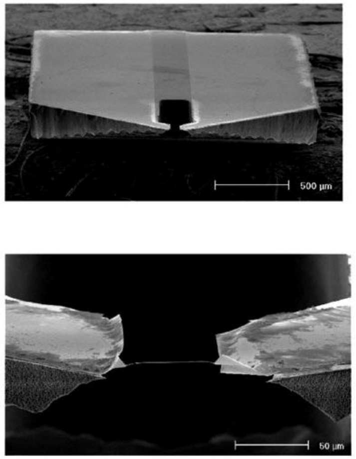


Li, McKeon, Jiang, Morrison and Smits MST (2004)

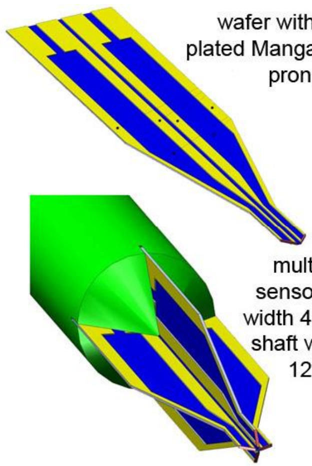
Sensor (spatial resolution)

- Etching process required to decrease the active length (silver sheat on platinum) creating the stubs
- Aerodynamic perturbation of the stubs (??)
- Final geometry of the wire (deformations)

Future probes



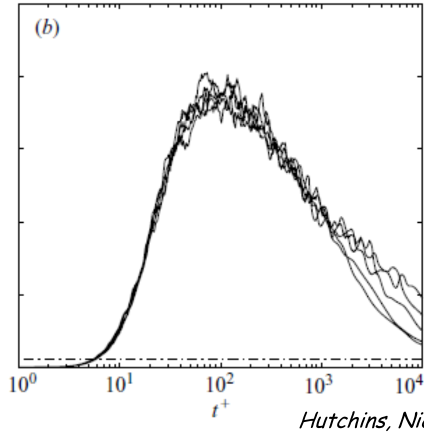
Kunkel and Smits



Libertzon et al.

Time response

- t+ < 3 (e.g. t+=3 corresponds to 100Khz once uτ > 2.1 m/s)



Hutchins, Nickels, Marusic and Chong JFM (2009)

Frequency response

- Dynamic calibration might be an issue if the Re is high and L/d small
  - Biot number and heat generation depend on time and axial position -> heat waves
- Heat waves can be minimised by using a high overheat ratio
- At low frequencies the wire temperature distribution is close to the mean

Effect of probe alignment error

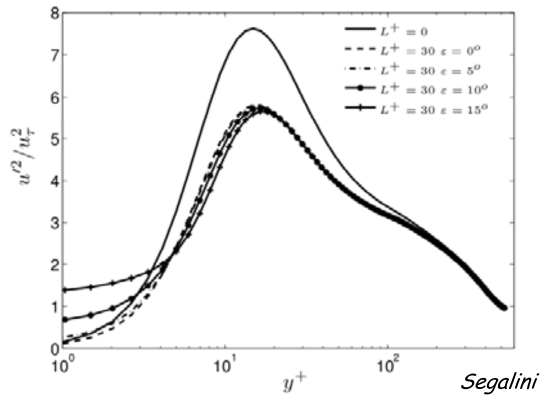
- The heat transfer has place in the whole wire length;
- If the wire is immersed in a wall bounded flow, probe misalignments (with respect to the wall plane) introduce small errors in the mean and rms of the measured streamwise velocity especially close to the wall;

$$\frac{\langle U\rangle_{meas}}{\langle U\rangle_{true}} = 1 + \varepsilon^2 \frac{L^2}{24\langle U_0\rangle}\frac{d^2\langle U\rangle}{dy^2}$$

- The error is significant for high wire length L, skew angle and local second derivative of the mean velocity or low local velocity U_0;

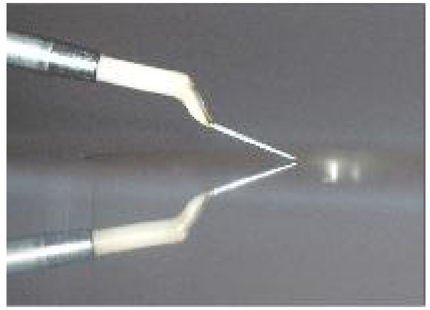
Effect of probe angle in the rms profile

- DNS simulation of a channel flow at Re_τ=550



Segalini et al. (2010)

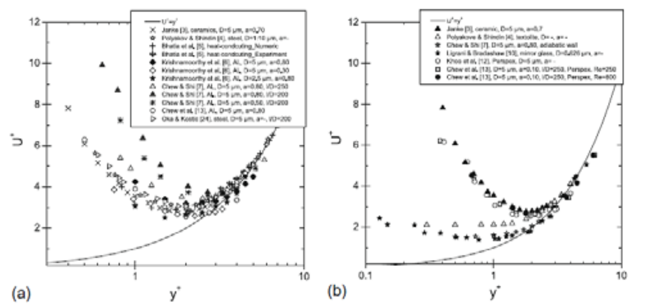
Blockage effects



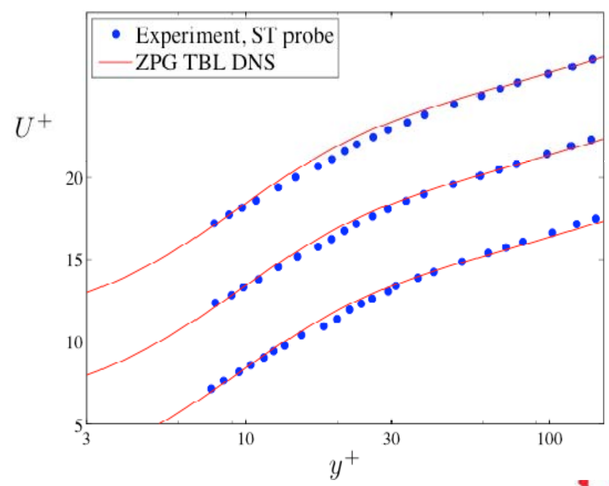
Wall interference

- Conduction important for y+<5
- The wall itself changes T field around the wire
- Corrections are dependent on wall conductivity and thickness, wire diameter, overheat ratio, shear velocity

- *Zanoun et al. 2009*



Blockage effects

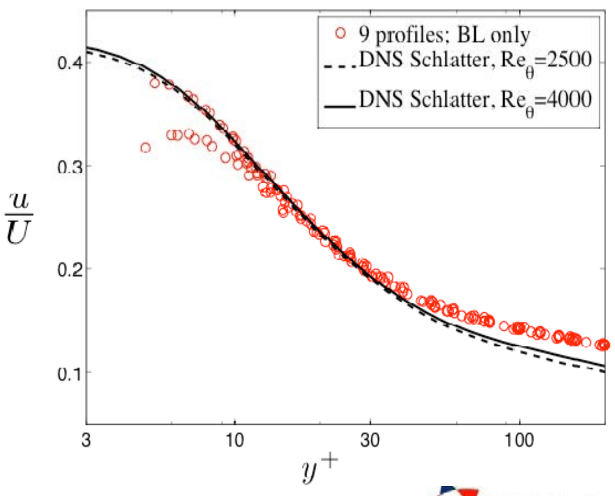


Blockage effects

$Re_\theta \approx 11500$

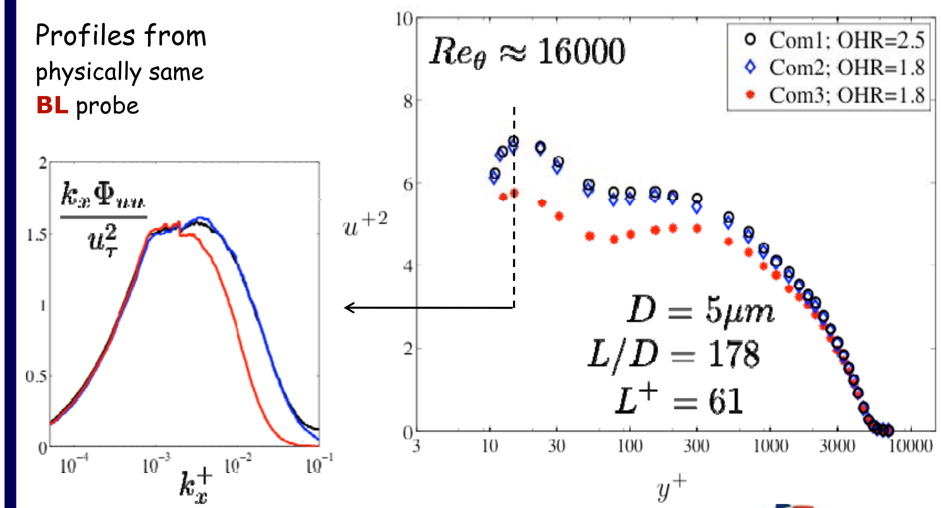
- Classical value for $\lim_{y^+ \to 0} u/U \simeq 0.4$
- HW generally measures lower values in the viscous sublayer, due to
  - spatial resolution
  - presence of wall

  as is the case for the **BL** probes



Effect of the anemometer (?)

Profiles from physically same **BL** probe

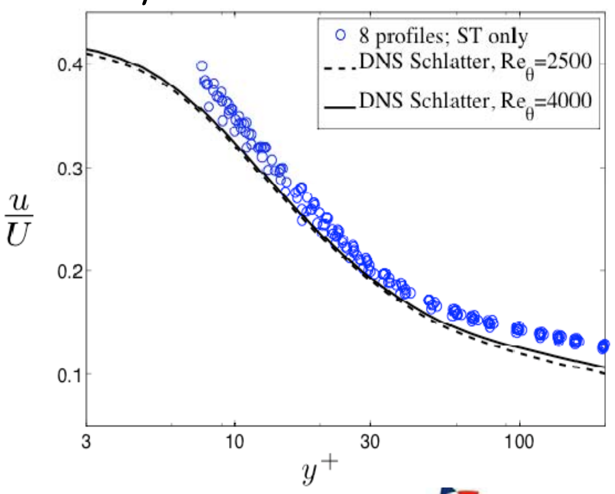


Blockage effects

ST probes

$Re_\theta \approx 11500$

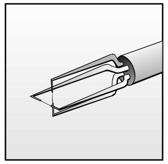
- Classical value for $\lim_{y^+ \to 0} u/U \simeq 0.4$
- **ST** probes measure, despite spatial averaging, too high r.m.s. levels in conjunction with too low mean velocities



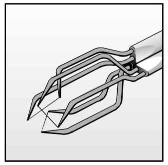
Multi component measurements

Commercial Probe types

- X-probes for 2D flows
  2 sensors perpendicular to each other. Measures within ±45°.



- Tri-axial probes for 3D flows
  3 sensors in an orthogonal system. Measures within 70° cone.



X - hot wire response (2)

Effective cooling velocity of sensor 1

$$U_{eff1}^2 = U_{N1}^2 + k^2 U_{T1}^2 = \frac{1}{2}\left[(U+u\pm v)^2 + k^2(U+u\mp v)^2 + 2h^2w^2\right]$$

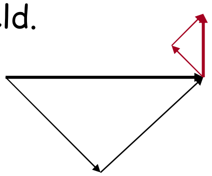
Similar equation for sensor 2 − +

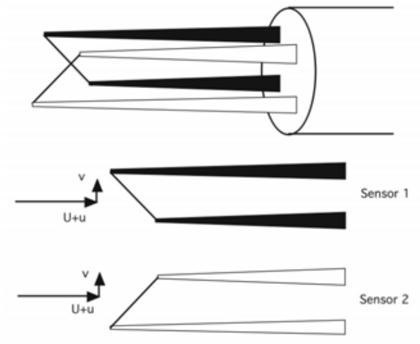
$$U_{xprobe} = \frac{U_{eff1}+U_{eff2}}{\sqrt{2(1+k^2)}} = U\left[1+\frac{u}{U}+\frac{k^2v^2+h^2w^2}{(1+k^2)U^2} + \text{h.o.t.}\right]$$

$$v_{xprobe} = \frac{U_{eff1}-U_{eff2}}{\sqrt{2(1+k^2)}} = v\frac{1-k^2}{1+k^2} + O(vw^2, v^3)$$

X - hot wire response (1)

Determine the normal and tangential components on the wires of the velocity field.

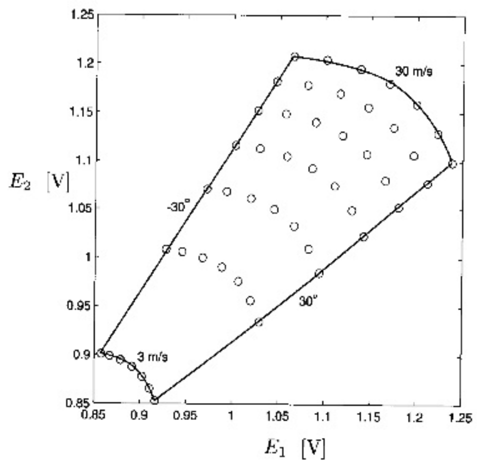




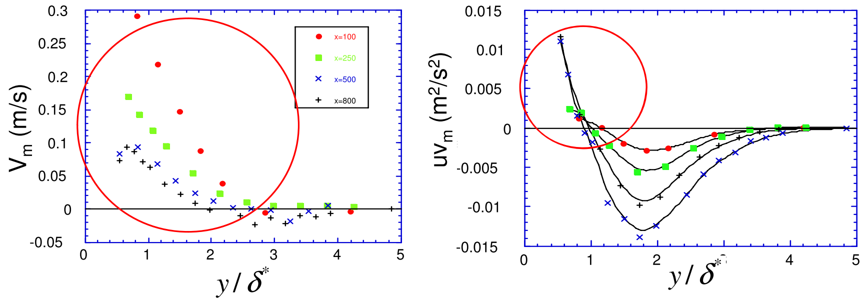
$$U_{N1} = \frac{U+u+v}{\sqrt{2}} \quad \text{and} \quad U_{T1} = \frac{U+u-v}{\sqrt{2}}$$ Sensor 1

$$U_{N2} = \frac{U+u-v}{\sqrt{2}} \quad \text{and} \quad U_{T2} = \frac{U+u+v}{\sqrt{2}}$$ Sensor 2

Angle calibration of X-probe

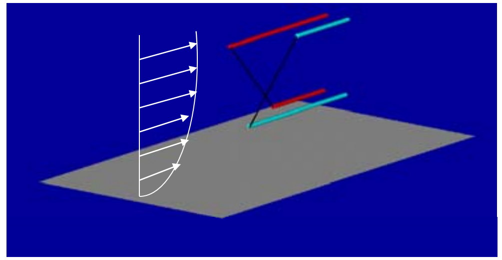


Errors



- Talamelli, Westin and Alfredsson (2000)

Shear effects: gradients parallel to the plane of the wires

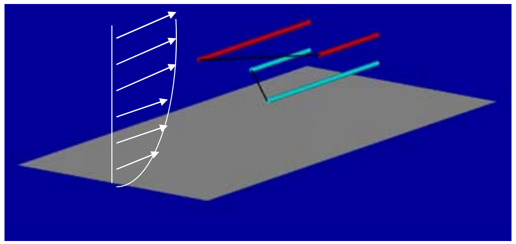


Small error due to the mean velocity gradient along each wire

Larger error if the wires are exposed to different velocity:

- Imperfections (physical displacement)
- Interference effects (virtual displacement)

Shear effects: gradients perpendicular to the plane of the wires

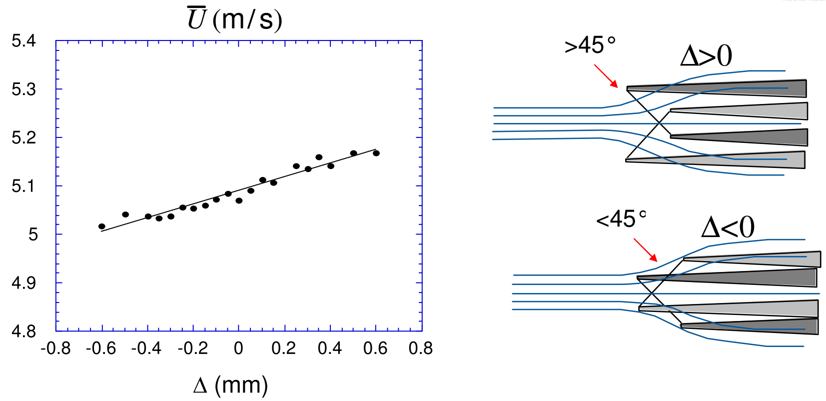


Assumption: local velocity is uniform over the probe volume

How to reduce gradient errors

- Minimize probe size
- Alternative probe types (V-probe, parallel wire probe, two X-wire probes)
- A posteriori correction (Cutler & Bradshaw, 1991)

Effect of probe configuration in U measured

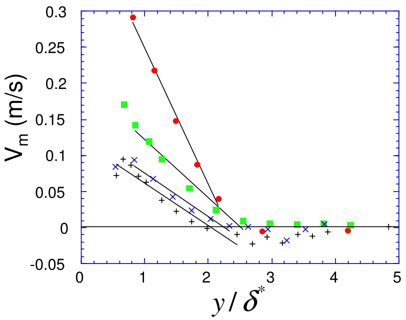


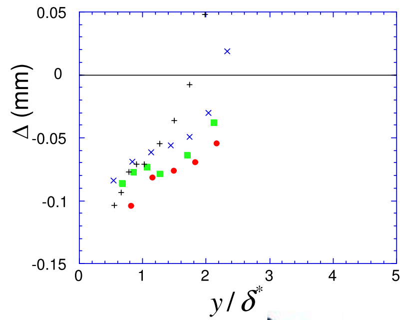
$$\overline{U}_m = \overline{U} + \frac{\Delta}{2}\frac{\partial \overline{V}}{\partial y} + \frac{1}{2}\left(\frac{\Delta}{2}\right)^2 \frac{\partial^2 \overline{U}}{\partial y^2} + O(\Delta^3)$$

Application to an experiment: Laminar boundary layer subjected to FST

- Assume that V≈0 inside boundary layer ⇒ measured V erroneous
- Calculate ∂U/∂y from measured profile
- Calculate a local virtual displacement Δ(y) using the 1st order correction

$$\overline{V}_m = \overline{V} + \frac{\Delta}{2}\frac{\partial \overline{U}}{\partial y}$$





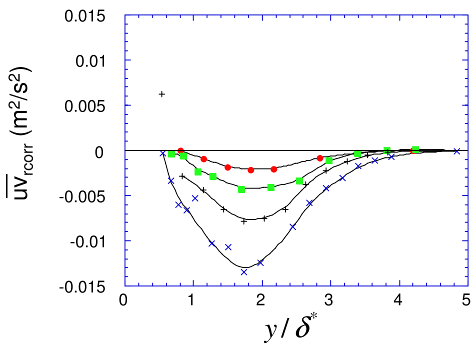
Laser Doppler anemometry (LDA)

DeGraaf and Eaton EXF (2001)
Experimental Fluid Mechanics SPRINGER HANDBOOK

Application to an experiment: Laminar boundary layer subjected to FST

- Calculate $\frac{\partial}{\partial y}(\overline{u^2}+\overline{v^2})$ from measured profiles
- Use the estimated displacement Δ(y) to correct $\overline{uv}$

$$\overline{uv}_m = \overline{uv} + \frac{\Delta}{4}\frac{\partial}{\partial y}(\overline{u^2}+\overline{v^2})$$

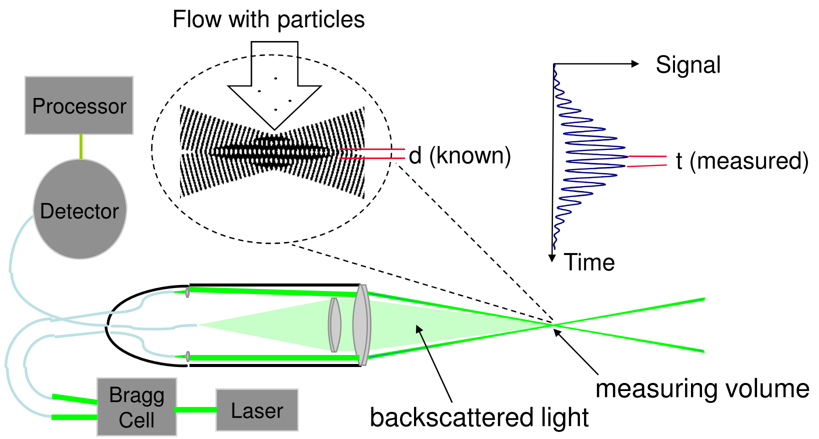


- more physically correct shape
- $\overline{uv}$-profile consistent with mean velocity distortion

Characteristics of LDA

- Velocity measurements in Fluid Dynamics (gas, liquid)
- Up to 3 velocity components
- Non-intrusive measurements (optical technique)
- Absolute measurement technique (no calibration required)
- Very high accuracy
- Very high spatial resolution due to small measurement volume
- Tracer particles are required

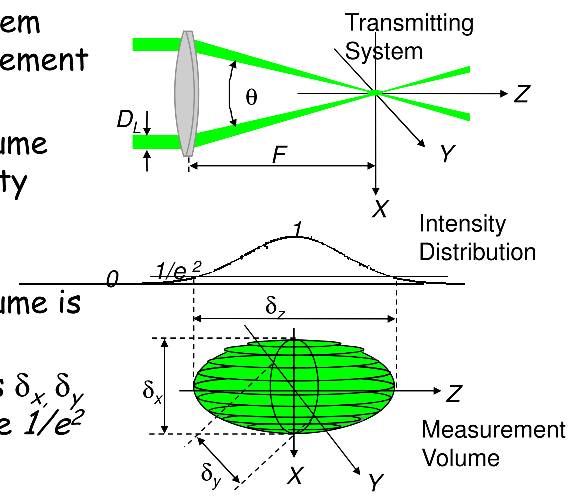
Velocity = distance/time



Courtesy of DANTEC

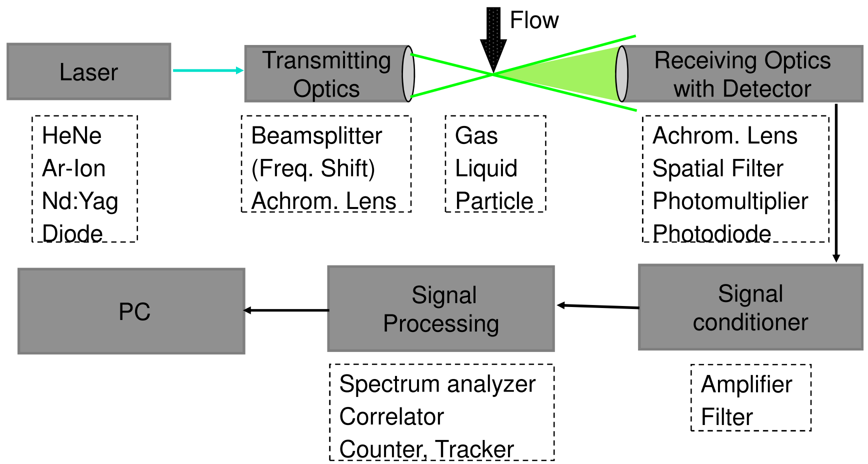
Measurement Volume

- The transmitting system generates the measurement volume
- The measurement volume has a Gaussian intensity distribution in all 3 dimensions
- The measurement volume is an ellipsoid
- Dimensions/diameters δ_x, δ_y and δ_z are given by the *1/e²* intensity points



Courtesy of DANTEC

Principle of LDA, the apparatus



Courtesy of DANTEC

Measurement Volume

Length:

$$\delta_z = \frac{4F\lambda}{\pi E D_L \sin\left(\frac{\theta}{2}\right)}$$

Width:

$$\delta_y = \frac{4F\lambda}{\pi E D_L}$$

Height:

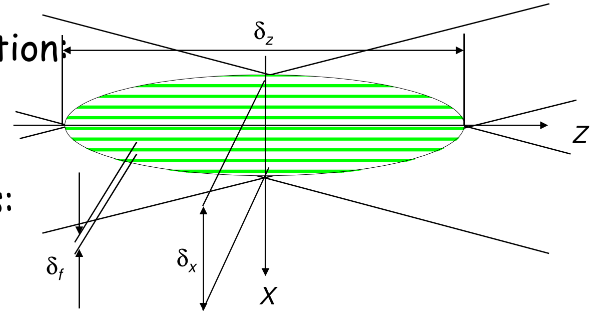
$$\delta_x = \frac{4F\lambda}{\pi E D_L \cos\left(\frac{\theta}{2}\right)}$$

Fringe Separation:

$$\delta_f = \frac{\lambda}{2\sin\left(\frac{\theta}{2}\right)}$$

No. of fringes:

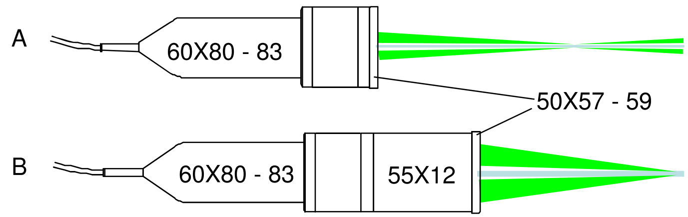
$$N_f = \frac{8F\tan\left(\frac{\theta}{2}\right)}{\pi E D_L}$$



Courtesy of DANTEC

Measurement volume

- *A Beam Expander* can be used to reduce probe volume



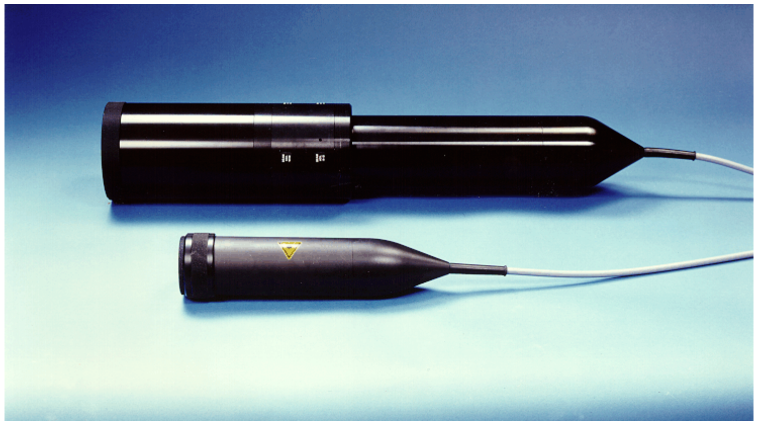
Seeding: ability to follow flow

Particle Frequency Response

$$\frac{d}{dt}U_p = -18\frac{\nu}{d_p^2}\frac{U_p - U_f}{\rho_p / \rho_f}$$

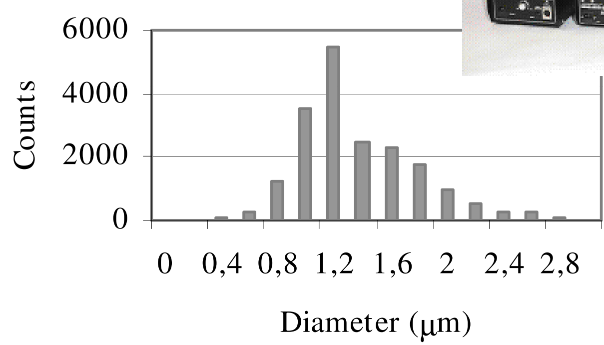
Particle	Fluid	Diameter (μm) f = 1 kHz	Diameter (μm) f = 10 kHz
Silicone oil	atmospheric air	2.6	0.8
TiO_2	atmospheric air	1.3	0.4
MgO	methane-air flame (1800 K)	2.6	0.8
TiO_2	oxygen plasma (2800 K)	3.2	0.8

The beam expander



Courtesy of DANTEC

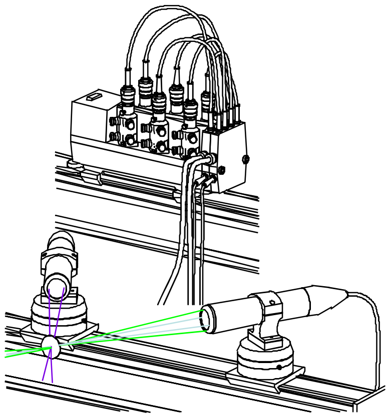
Seeding: distribuzione dimensioni (Safex smoke)



Courtesy of DANTEC

FiberFlow setup for 3-D velocity measurements

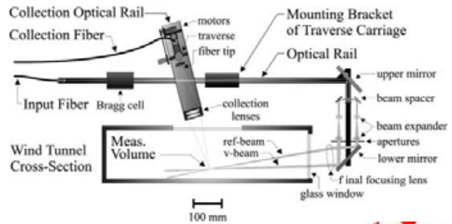
- Measuring three velocity components requires three beam pairs.
  - Two pairs are emitted from a 2D probe
  - One pair from a 1D probe
- The two probes are aligned so their intersection volumes coincide.
- The velocity components measured by the beams from the 2D probe are orthogonal.
- The third velocity component can be orthogonalized by software.



Courtesy of DANTEC

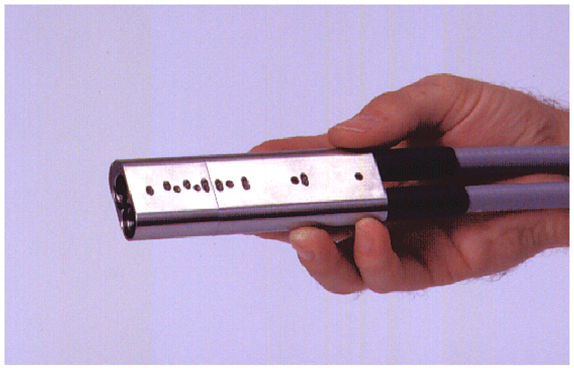
LDA for high Re

- Non intrusive
- Operates in highly turbulent flows
- Better resolution than hot-wire
- Standard commercial volumes (150 microns – 1 mm)
- Less with "ad hoc" apparatus



DeGraaf and Eaton EXF (2001)

The small integrated 3D *FiberFlow* probe



Courtesy of DANTEC

Problems in wall measurements

- Compact probes or small mirrors suspended in the flow (vibration, probe interference,..)
- Bias related to the particle arrival rate proportional to fluid velocity
- Bias due to accuracy of high velocity
- To avoid bias high seeding density and computer controlled sampling – Not possible close to the wall
- Alignment of individual beams (waist position must collapse with the crossing point)

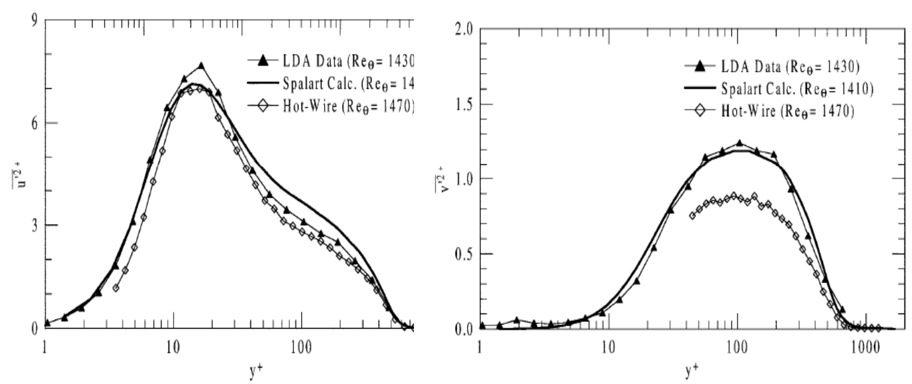
Problems in wall measurements

- Acquisition in side scatter
- Problems to locate the measurement volume
- Keep the measurement point stable (isolate vibrations)
- Use of slots

Time resolved pressure measurements

McKeon and Smits MST (2002)
McKeon, Li, Jiang, Morrison and Smits MST (2003)
Experimental Fluid Mechanics SPRINGER HANDBOOK

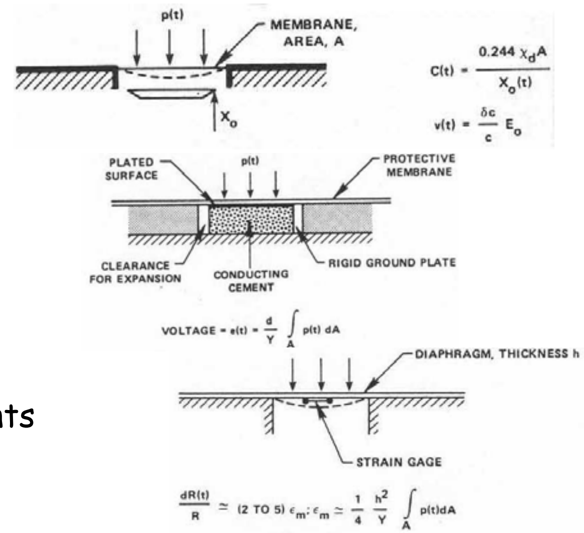
Stress profiles



DeGraaf and Eaton EXF (2001)

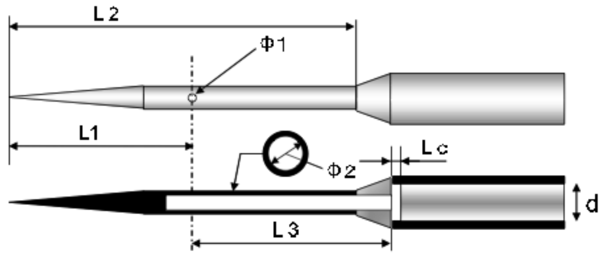
The transducers

- Capacitive type
- Piezoelectric type
- strain measurements



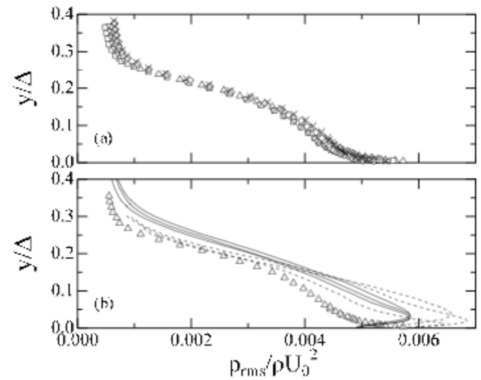
A new probe for tbl measurements

Pressure probe for measurements of pressure fluctuations inside the boundary layer (Tsuji et al 2007)



Time resolved pressure measurements

Measured rms fluctuations of the pressure inside turbulent boundary layers at different Re. Lines are from numerical simulations.



Frequency response

Frequency response for pressure probe of Tsuji et al. Frequenct is normalized with Helmholz resonator frequency.