Advanced Experimental Methods : Fluid

Velocimetry

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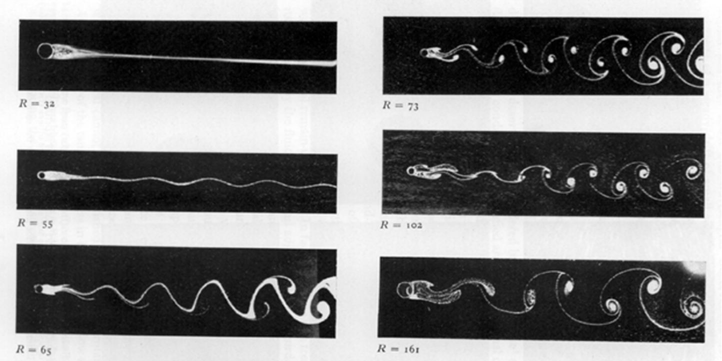
Why measuring the velocity ?

- Reveal "structures" in the flow.



- Solution of the Navier-Stokes equations.

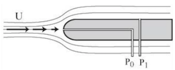
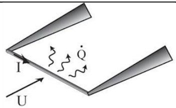
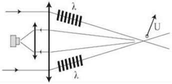
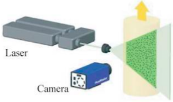
How to measure the velocity ?

- Concept of *fluid particle*.
- Seeding :

  Ink

  Bubles or smokes

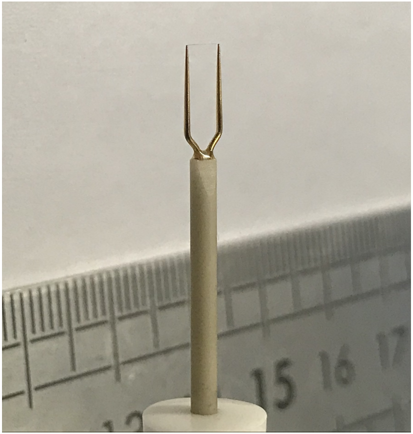
Different techniques of velocimetry

	Pitot tube	**Hot wire anemometry** (HWA)	**Laser Doppler Velocimetry** (LDV)	**Particle Image Velocimetry** (PIV)
Scheme				
Principle	Bernoulli's equation based on the static and dynamic pressures $U = \sqrt{2(p_T - p_s)/\rho}$	based on the power dissipated RI^2 by a heated wire	Interferometric measure of the Doppler shift on a scattering particle	Correlation between two images of seeding particles
Advantages	Simple to implement. Cheap ($\mathcal{O}$(1 k€)). Ideal for mean velocity profiles.	Excellent spatial & temporal resolutions. Rather simple to implement. Reasonably expensive ($\mathcal{O}$(3-5 k€))	Non intrusive. Linear calibration. Very good spatial & temporal resolutions. Possibility for more than one velocity component.	Non intrusive. Instantaneous 2D field.
Drawbacks	Very intrusive. Weak spatial & temporal resolution	Intrusive. Fragile. Non-linear calibration. Contaminations (temperature fluctuations)	Optical access and transparent fluid. Seeding particles. Fine adjustments. Expensive $\mathcal{O}$(10-50 k€).	Optical access and transparent fluid. Seeding particles. Weak temporal resolution (standard PIV). Very expensive $\mathcal{O}$(50-100 k€).

Outline

Hot wire anemometry

Hot wire anemometry : how does it look like ?



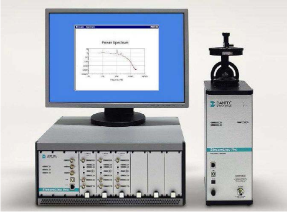
platinium or tungstene thin wire (few microns thick, few mm long)
welded to the prongs of the probe support

Range of devices

"pocket-size" model
(mean velocity)

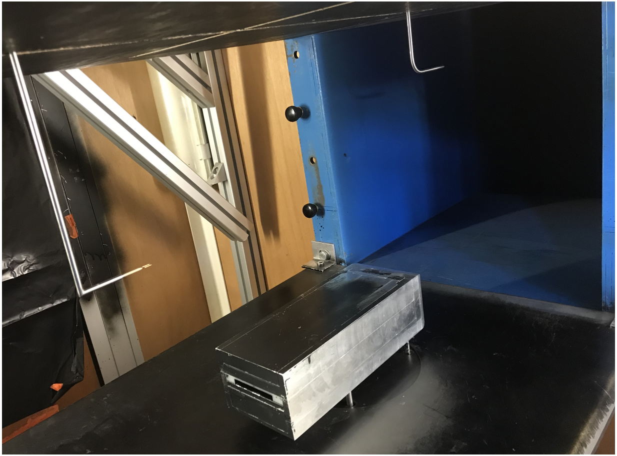
(Testo)
150 - 400 €

"lab" model
(instantaneous velocity)



DANTEC
1 000 -10 000 €

Hot wire anemometry : how does it work ?



- Heat is generated when a current passes through the wire, balanced by heat loss (primarily convective) to the surroundings in equilibrium.
- If velocity changes, convective heat transfer coefficient will change, wire temperature will change and eventually reach a new equilibrium.

Governing Equations

If E is the thermal energy stored in the wire

$$\boxed{\frac{dE}{dt} = \dot{W} - \dot{Q}}$$

— $\dot{W} = R_w I^2$ is the power generated by Joule heating,

— $\dot{Q}$ the heat transferred to surroundings *via*

→ Convection to the fluid :

$$\dot{Q}_{cnv} = h\mathcal{A}(T_w - T_0) = \pi \ell k_f Nu (T_w - T_0)$$

with $Nu = h\phi/k_f$ the Nusselt number, ϕ the wire diameter,
$\mathcal{A} = 2\pi\ell(\phi/2)$ the wire area,
h heat transfer coefficient,
k_f heat conductivity of the fluid

→ Conduction to the fluid and to supports ;

→ Radiation to surroundings :

$$\dot{Q}_{rad} = \sigma\mathcal{A}(T_w^4 - T_0^4),$$

with the Stefan constant $\sigma = 5.7 \times 10^{-8}\,\mathrm{W{\cdot}m^{-2}{\cdot}K^{-4}}$

The King's law

The Nusselt number is function of many parameters

$$Nu = f(Re_w; Pr, Ma, \ell/\phi, R_w/R_0)$$

where $Re_w = U\phi/\nu_f$ is the Reynolds number associated with the wire diameter and U the velocity a few ϕ upstream of the wire, ν_f the fluid viscosity at $T_f = (T_w + T_0)/2$.

In a regime of forced convection where $Pr = \nu/\kappa \approx 1$, $\ell/d \gg 1$, the **King's law** (1914) for an apparent potential stationary 2D flow reads

$$\boxed{Nu = 1 + \sqrt{2\pi Re_w}.}$$

The law in $Re_w^{1/2}$ is typical of heat transfers in laminar flows !

Stationarity is satisfied if the time scale of the turbulent fluctuations $\tau \ll \phi/U$, where the time of advection along the wire $\phi/U \approx 0.5\,\mu$s ($U/\phi \approx 2\,$MHz).

In practice,

$$Nu = a_0(Pr, Ma, \ell/d, \ldots) + b_0(Pr, Ma, \ell/d, \ldots)\sqrt{Re_w}.$$

Probe resistance

The wire resistance R_w changes with T_w.

$$R_w = R_0 \left(1 + \beta(T_w - T_0)\right)$$

where

$$\beta = \frac{1}{R_w} \frac{\partial R_w}{\partial T}$$

is reasonably constant over a large range of T.

For Pt or tungstene, $\beta \approx 5 \times 10^{-3}\,\mathrm{K}^{-1}$.

The King's law becomes

$$\boxed{\frac{R_w I^2}{R_w - R_0} = a + b\sqrt{U}.}$$

i.e., with $e = R_w I$

$$\frac{e^2}{R_w(R_w - R_0)} = a + b\sqrt{U}.$$

Two strategies

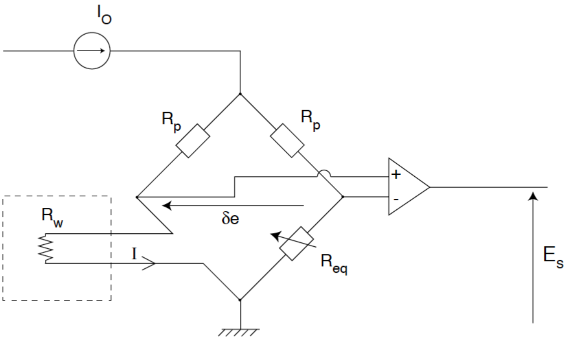
— Keep the current I constant and measure U through the fluctuations of R_w only

Constant Current Anemometer (CCA) : today obsolete.

— Keep the resistance R_w constant, and thus the wire temperature T_w constant, and measure U through the fluctuations of I

Constant Temperature Anemometer (CTA).

Constant Current Anemometer (CCA)

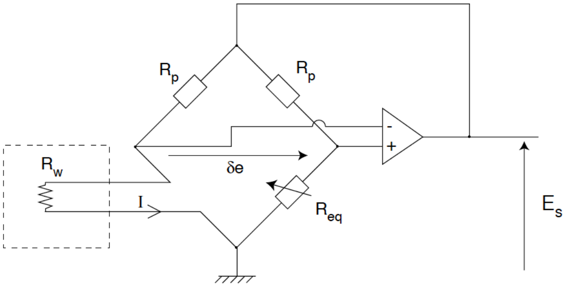


The bridge is initially balanced ($\delta e = 0$ when $U = 0$), unbalanced when R_w varies because of the flow, with I_O constant

$$\delta e = (R_w - R_{eq})I = I\delta R_w, \qquad E_s = G\delta e, \qquad G \approx 10^3$$

Drawback : frequency range limited to $\approx 700\,\mathrm{Hz}$ as the time scale to thermal equilibrium due to T_w variations should be much shorter than the time scales of the flow fluctuations.

Constant Temperature Anemometer (CTA)



The bridge is initially unbalanced ($R_{eq} \neq R_w$) with an **overheat coefficient**

$$\alpha = R_w / R_{eq} > 1$$

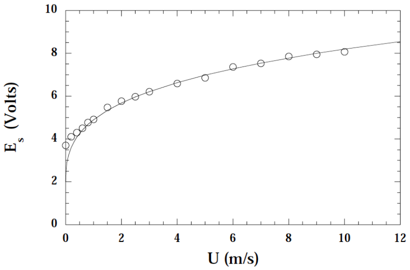
R_w is kept constant at $T_w = T_0 + (\alpha - 1)/\beta$ through a negative feedback loop ($E_s = -\delta e$), where

$$\delta e = \sqrt{R_w(R_w - R_0)(a + b\sqrt{U})}$$

$$\boxed{E_s = \sqrt{A + B\sqrt{U}}.}$$

Calibration

The King's law is non-linear, which requires a careful calibration of the probe



A **modified King's law** is usually better suited

$$E_s^2(U) = A + BU^n$$

with n usually between 0.4 and 0.6. The coefficients are determined as

$$A = E_s^2(0)$$

$$n \log U + \log B = \log(E_s^2(U) - A)$$

Empirical relation

Collis & Williams (1959)'s empirical relation

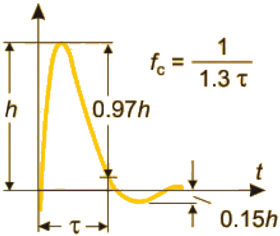
$$\begin{aligned} n = 0.45 \quad &\text{for} \quad 0.02 < Re_w < 44, \\ n = 0.51 \quad &\text{for} \quad 44 < Re_w < 140. \end{aligned}$$

Why so ?

The wire can be seen as a cylinder in a cross-flow

- $Re_w < 44$, the wake is steady and symmetric.
- $Re_w > 44$, the wake becomes non-symmetric and unsteady with the cyclic release of vortices : heat transfers are enhanced.
- $Re_w > 140$, the wake becomes disordered, heat transfers become even better.

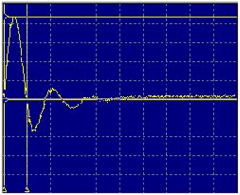
Frequency response



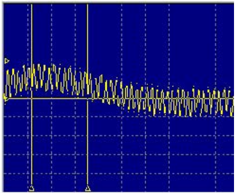
The bandwidth is defined as the inverse of the time at which the signal amplitude is damped by $-3\,\text{dB}$,

$$f_c = 1/1.3\tau$$

CCA	$\approx 700\,\text{Hz}$
CTA	$\approx 1\,\text{MHz}$ reduced to 10-100 kHz by the spatial resolution (ℓ)



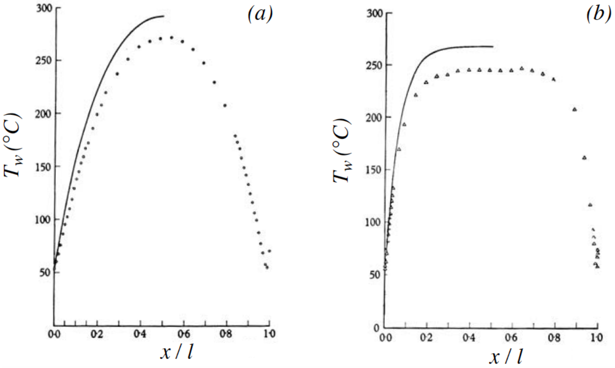
too high gain



too long cable (10 m instead of 5 m)

Finite length effect

Conduction by support $\Rightarrow$ non-uniform temperature distribution along the wire

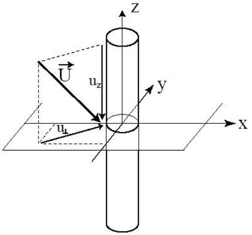


$\ell/\phi \approx 100$ $\qquad$ $\ell/\phi \approx 400$

(From Champagne et al (1967), reproduced by Lomas (1986))

A usual compromise is $\ell \approx 1\,\text{mm}$, $\phi \approx 5\,\mu\text{m}$

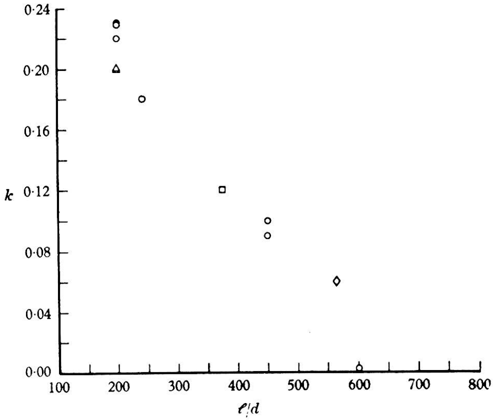
Directional sensitivity



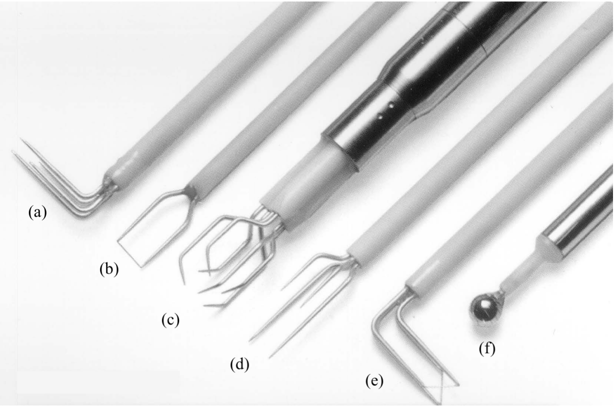
Velocity component actually implied in heat transfers to the fluid

$$U_{eff}^2 = \sqrt{u_\perp^2 + k^2 u_z^2}$$

When $\ell/\phi \to \infty$, $k \to 0$
When $\ell/\phi \to 1$, $k \to 1$



Different probes



- X Anemometers : two (or more) crossed anemometers to measure two (or more) velocity components (a,c,e)
- Anemometers with cold probe to compensate temperature fluctuations in the flow (d)
- Hot film anemometers with nickel coating on a quartz support (f).

Hot wire anemometry : main features

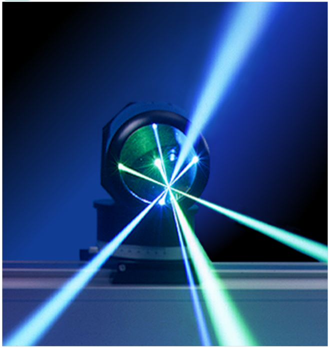
- Time-resolved "point" measurement (0D).
- Intrusive and fragile.
- Mainstream flow.
- Non-linear law in the convective regime (modified King's law) :

$$E_s^2(U) = A + BU^n$$

- Directional ambiguity.

Laser Doppler Velocimetry

DANTEC DYNAMICS



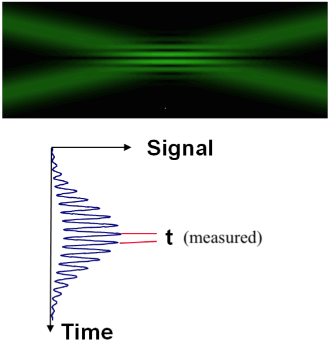
Inventeurs : Yeh & Cummins (1964)

Laser Doppler Velocimetry / hot wire comparison

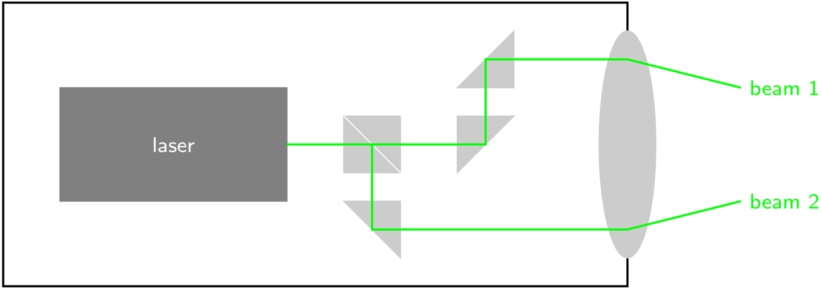
Hot wire	**LDV**
0D	0D
Time-resolved	Time-resolved
Intrusive	Non-intrusive
Fragile	Robust
Non-linear law	Linear law
Directional ambiguity	Directional ambiguity manageable
Reasonably expensive	Expensive

Laser Doppler Anemometry : the fringe model

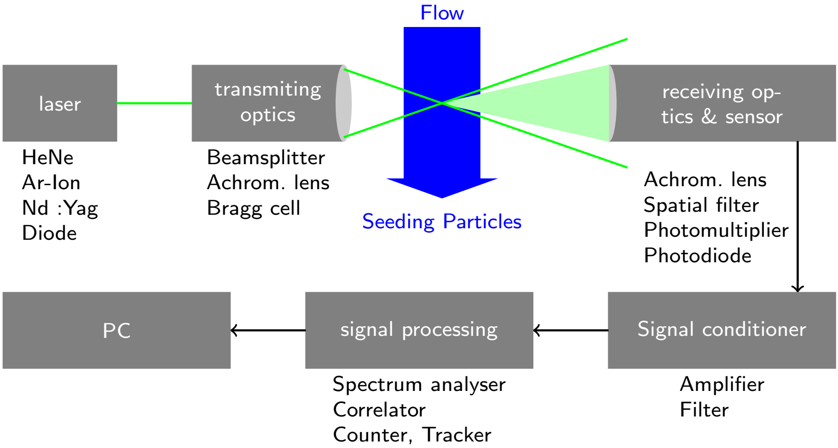
Principle



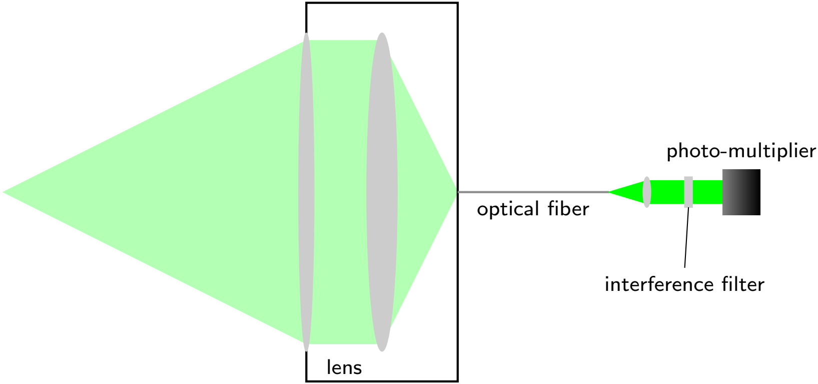
Transmitting optics



Measurement line



Detection system



Why a laser ?

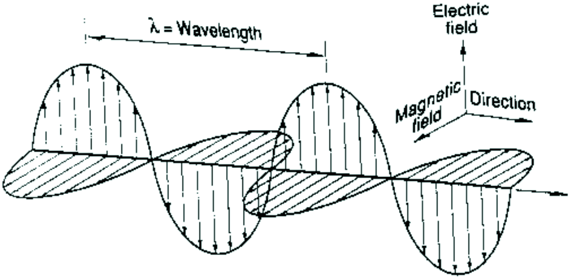
- Monochromatic
- Coherent
- Linearly polarised
- Collimated
- Gaussian intensity distribution

Some usual laser

- Argon laser
  Continuous power ; one of the four green-blue colors can be used : 514.5 nm, 496.5 nm, 488.0 nm 476.5 nm
- Helium laser
  Continuous He laser emitting in the red at 632.8 nm.
- YAG Laser
  Pulse emission in the infrared, providing, after doubling the frequency, a wavelength at 532 nm.

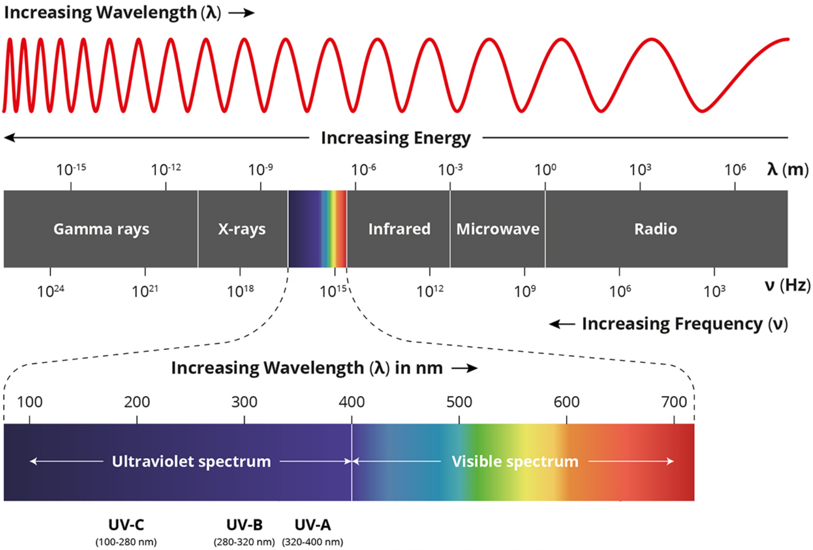
LASER	λ (nm)	color	power (mW)	diameter (mm)
He-Ne (gas)	632.8	red	1-15	0.65
Ar^{2+} (gas)	476.5	violet	1-600	1.5
	488	blue	1-1500	1.5
	514.5	green	1-2000	1.5
doubled YAG (solid)	532	green	20-2000	1

The electro-magnetic vibration



$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{p} E_0 \cos(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi) \equiv \boldsymbol{p}\,\Re\left(E_0 e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r})}\right)$$

One spectrum, many colors



Why does light interfere ?

Both vibrations sum up, intensity is measured

$$I(\boldsymbol{r},t) = |\boldsymbol{E}_1(\boldsymbol{r},t) + \boldsymbol{E}_2(\boldsymbol{r},t)|^2 = |E_1\boldsymbol{p}_1 \cos(\omega_1 t - \boldsymbol{k}_1\cdot\boldsymbol{r}) + E_2\boldsymbol{p}_2 \cos(\omega_2 t - \boldsymbol{k}_2\cdot\boldsymbol{r})|^2$$

If $\omega_1 = \omega_2$ then $k_1 = k_2$ but $\boldsymbol{k}_1 \neq \boldsymbol{k}_2$

$$\begin{aligned} I(\boldsymbol{r},t) = {} & E_1^2\cos^2(\omega t - \boldsymbol{k}_1\cdot\boldsymbol{r}) + E_2^2\cos^2(\omega t - \boldsymbol{k}_2\cdot\boldsymbol{r}) \\ & + E_1E_2\,\boldsymbol{p}_1\cdot\boldsymbol{p}_2\,\left(\cos((\boldsymbol{k}_2-\boldsymbol{k}_1)\cdot\boldsymbol{r}) + \cos(2\omega t - (\boldsymbol{k}_2+\boldsymbol{k}_1)\cdot\boldsymbol{r})\right) \end{aligned}$$

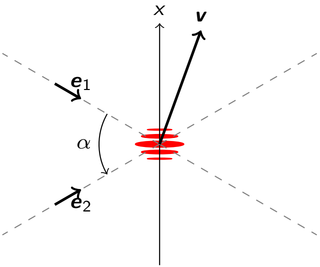
At the scale of the sensor time response τ

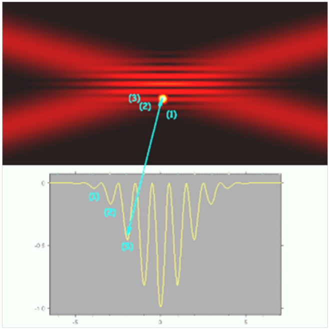
$$\langle I(\boldsymbol{r},t)\rangle_\tau = I_0 + \gamma\,\underbrace{\cos((\boldsymbol{k}_2-\boldsymbol{k}_1)\cdot\boldsymbol{r})}_{\text{interference network}}$$

Spatially structured, independent of time.
γ max when $\boldsymbol{p}_1 = \pm\boldsymbol{p}_2$

Interfringe of the interference network

$$\langle I(\boldsymbol{r},t)\rangle_\tau = I_0 + \gamma\cos\left((\boldsymbol{k}_2-\boldsymbol{k}_1)\cdot\boldsymbol{r}\right)$$

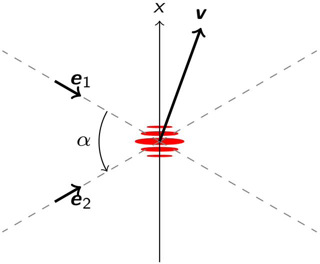


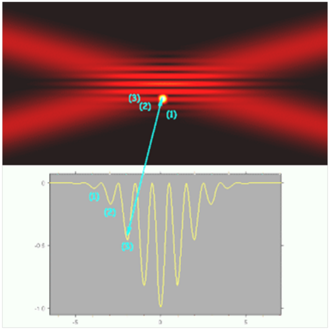


Exercise : determine the interfringe d.

Interfringe of the interference network

$$\langle I(\boldsymbol{r},t)\rangle_\tau = I_0 + \gamma \cos\left((\boldsymbol{k}_2-\boldsymbol{k}_1)\cdot\boldsymbol{r}\right)$$





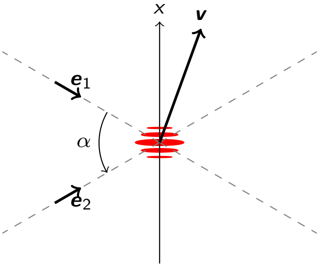
Exercise : determine the interfringe d.

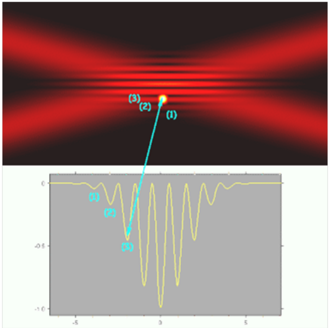
$$(\boldsymbol{k}_2-\boldsymbol{k}_1)\cdot\boldsymbol{r} = \frac{2\pi}{\lambda}(\boldsymbol{e}_2-\boldsymbol{e}_1)\cdot\boldsymbol{r} = \frac{2\pi}{\lambda}2x\sin\left(\frac{\alpha}{2}\right) \quad\Rightarrow\quad 2\pi = \frac{2\pi}{\lambda}2d\sin\left(\frac{\alpha}{2}\right)$$

$$d = \frac{\lambda}{2\sin\frac{\alpha}{2}}$$

What do we measure ?

Seeding particles pass through the fringes with velocity $\boldsymbol{v}$.





The light scattered by the seeding particles is modulated in time with period

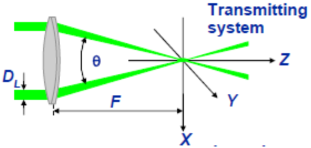
$$T_D = \frac{d}{\boldsymbol{v} \cdot \boldsymbol{e}_x}$$

or frequency

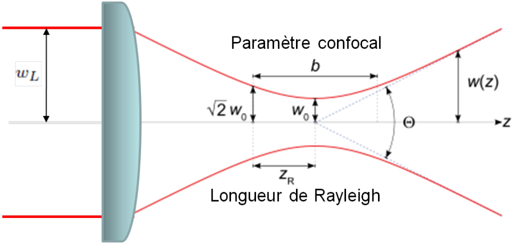
$$f_D = \frac{2V_x}{\lambda} \sin \frac{\alpha}{2}.$$

The measurement point in fact is a volume

Measurement volume



Limit of diffraction of a gaussian beam

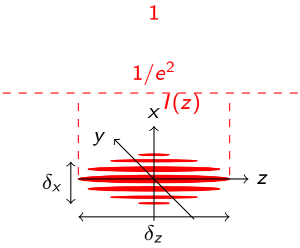


$$w_0 = \frac{\lambda f}{\pi w_L}$$

$$z_R = \frac{\pi w_0^2}{\lambda}$$

$$\Theta = 2\theta \simeq \frac{2\lambda}{\pi w_0}$$

Characteristics of the measurement volume



Volume dimensions

$$\delta_z = \frac{4f\lambda}{\pi D_L \sin\frac{\alpha}{2}}, \qquad \delta_y = \frac{4f\lambda}{\pi D_L}, \qquad \delta_x = \frac{4f\lambda}{\pi D_L \cos\frac{\alpha}{2}}$$

Interfringe

$$d = \frac{\lambda}{2\sin\frac{\alpha}{2}}$$

Number of fringes

$$N = \frac{8f\tan\frac{\alpha}{2}}{\pi D_L}$$

Residing time in the measurement volume

$$\Delta t = \frac{\delta_x}{V_x} \qquad \Rightarrow \qquad f_s = 1/\Delta t$$

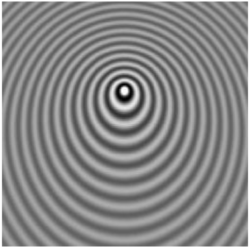
V_x particle velocity and δ_x measurement volume dimension along x.
For V_x fixed, the sampling frequency f_s is increased when δ_x is decreased

Laser Doppler Anemometry : the Doppler effect

With a single beam...

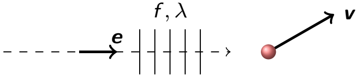
... it would also works !

What is the Doppler effect ?



Doppler effect

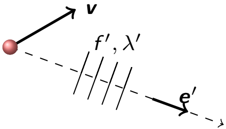
- Still source, moving particle (observer)



Distance between two emitted fronts at T by the source	$\lambda = cT$
Distance covered by the particle between 2 source impulsions	$\ell = \boldsymbol{v} \cdot \boldsymbol{e}\, T'$
Distance covered by the 2nd impulsion during T'	$\lambda' = \lambda + \ell = cT'$

$$\Rightarrow \qquad T'\left(1 - \frac{\boldsymbol{v} \cdot \boldsymbol{e}}{c}\right) = T \qquad \text{and} \qquad f' = \left(1 - \frac{\boldsymbol{v} \cdot \boldsymbol{e}}{c}\right) f$$

- Moving source (particle), still receptor



$$\Rightarrow \qquad T''\left(1 + \frac{\boldsymbol{v} \cdot \boldsymbol{e}'}{c}\right) = T' \qquad \text{and} \qquad f'' = \left(1 + \frac{\boldsymbol{v} \cdot \boldsymbol{e}'}{c}\right) f'$$

The Doppler shift

Emission/reception relation

$$f'' = \left(1 - \frac{\boldsymbol{v} \cdot \boldsymbol{e}}{c}\right) \left(1 + \frac{\boldsymbol{v} \cdot \boldsymbol{e}'}{c}\right) f$$

Doppler shift

$$f_D = f'' - f \simeq f \, \frac{\boldsymbol{v}}{c} \cdot (\boldsymbol{e}' - \boldsymbol{e}) \qquad \text{if} \quad \frac{v}{c} \ll 1$$

Estimate the value of f_D

The Doppler shift

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$$f \sim 10^{14} \;\; Hz, \qquad f_D \sim 10^6 - 10^7 \;\; Hz$$

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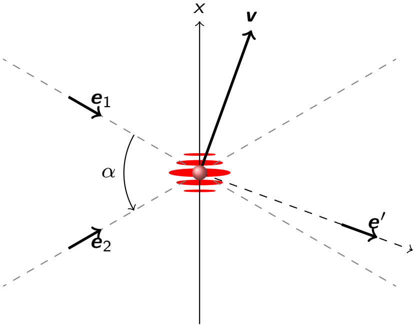
Estimate the value of f_D

$$f \sim 10^{14} \ Hz, \qquad f_D \sim 10^6 - 10^7 \ Hz$$

⇒ a direct measurement of f'' would require a device of resolution 10^{-8} for a precision of only 10%.

⇒ a direct measurement of f_D is preferred with a interference system.

Doppler shift on crossed beams



$$f_1 \simeq f\left(1 - \frac{\mathbf{v}}{c} \cdot (\mathbf{e}_1 - \mathbf{e}')\right)$$

$$f_2 \simeq f\left(1 - \frac{\mathbf{v}}{c} \cdot (\mathbf{e}_2 - \mathbf{e}')\right)$$

Recombination of crossed beams

Intensity at the sensor : $I(t) = |\boldsymbol{E}_1(t) + \boldsymbol{E}_2(t)|^2$

Detected intensity : $i(\tau) = \langle I(t) \rangle_\tau = \frac{E_1^2}{2} + \frac{E_2^2}{2} + E_1 E_2 \cos\left((\omega_1 - \omega_2)\tau\right)$

Doppler shift :

$$\omega_1 - \omega_2 = 2\pi(f_1 - f_2) = 2\pi f \left(\frac{\boldsymbol{v}}{c} \cdot (\boldsymbol{e}_2 - \boldsymbol{e}_1) \right) = 2\pi \frac{f}{c} \left(2 V_x \sin \frac{\alpha}{2} \right) = 2\pi f_D$$

$$\Rightarrow \qquad f_D = f_1 - f_2 = f \left(\frac{\boldsymbol{v}}{c} \cdot (\boldsymbol{e}_2 - \boldsymbol{e}_1) \right)$$

- one component detected : $\frac{\boldsymbol{v}}{c} \cdot (\boldsymbol{e}_2 - \boldsymbol{e}_1) = \frac{V_x}{c} 2 \sin \frac{\alpha}{2}$
- no Doppler shift if $\boldsymbol{v}$ has no component along x
- measurement independent of the direction of detection $\boldsymbol{e}'$

Seeding particles

For liquids

State	Material	Mean diameter (μm)
Solid	polystyrene	10-100
	Aluminium	2-7
	hollow glass sphere	10-100
	granules for synthetic coating	10-500
Liquid	oils	50-500
Gas	bubles of O_2, H_2, etc	50-1000

For gas

State	Material	Mean diameter (μm)
Solid	polystyrène	0.5-10
	Aluminium	2-7
	Magnesium	2-5
	synthetic granules	1-10
	glass microbeads	30-100
Liquid	oils	0.5-10
	dioctylphathalate	< 1

Particle dynamics in the flow

Diluted spherical particles (negligible effect on the flow)

$$\underbrace{\frac{\pi}{6}\phi^3\rho_p\frac{d_p}{dt}\boldsymbol{v}_p}_{\text{inertial force}} = \underbrace{-3\pi\mu\phi(\boldsymbol{v}_p - \boldsymbol{v}_f)}_{\text{Stokes force}} - \frac{\pi\phi^3}{6}\underbrace{\nabla P}_{\rho\frac{d\boldsymbol{v}_f}{dt}}$$

$$- \underbrace{\frac{1}{2}\frac{\pi}{6}\phi^3\rho_f\left(\frac{d\boldsymbol{v}_f}{dt} - \frac{d_p\boldsymbol{v}_p}{dt}\right)}_{\text{fluid resistance to sphere acceleration}}$$

$$+ \underbrace{\frac{3}{2}\phi^2\sqrt{\pi\rho_f\mu}\int_0^t \frac{1}{\sqrt{t-t'}}\left(\frac{d\boldsymbol{v}_f}{dt} - \frac{d_p\boldsymbol{v}_p}{dt}\right)dt'}_{\text{drag force due to an unsteady flow}} + \boldsymbol{f}_{ext}$$

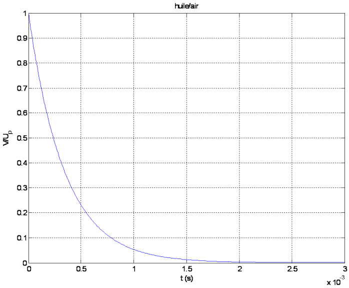
Dynamics of relaxation

$$\frac{d_p}{dt}\boldsymbol{v}_p = 18\frac{\mu}{\phi^2\rho_p}(\boldsymbol{v}_f - \boldsymbol{v}_p)$$

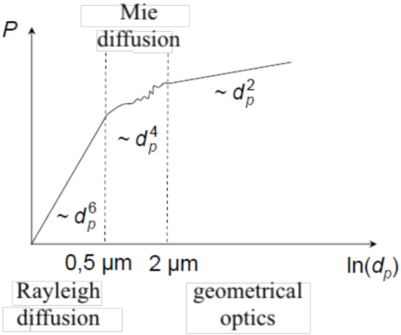
$$\Downarrow$$

$$\boldsymbol{v}_p = \boldsymbol{v}_f\left(1 - e^{-t/\tau_p}\right) \qquad \text{with} \qquad \tau_p = \frac{\rho_p\phi^2}{18\mu}$$

Particle	Fluid	Diameter (μm)	
		1 kHz	10 kHz
Silicone oil	atmospheric air	2.8	0.8
TiO_2	atmospheric air	1.3	0.4
MgO	methane-air flame (1 800 K)	2.6	0.8
TiO_2	oxygen plasma (2 800 K)	3.2	0.8



Regimes of diffusion



Light diffusion by the particles

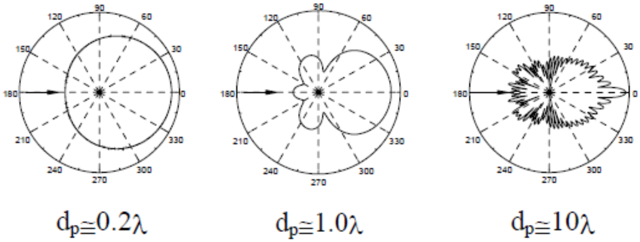
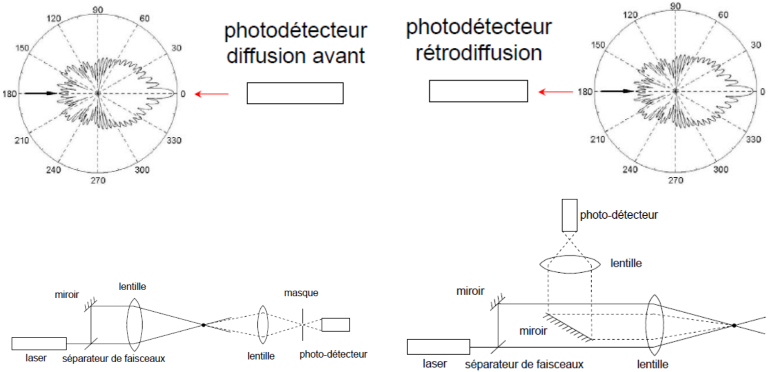
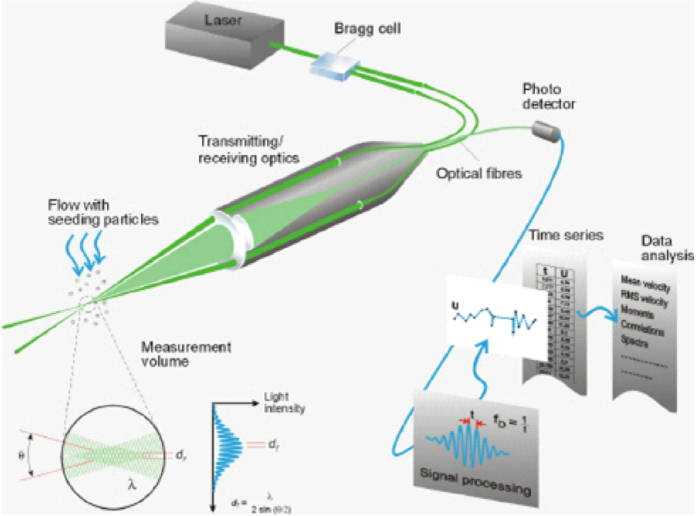


FIGURE – Polar representation of diffracted light intensity (on a logarithmic scale) *vs* angle of diffraction.

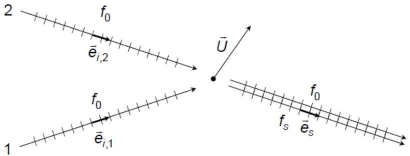
Forward and backward diffusion



Backscatter configuration



Reference beam mounting



- Historically first operating mode
- Doppler frequency extracted by optical heterodyne detection
- Photodetector must be aligned with the reference beam
- Only detect a small amount of diffused light (the fringe setup allows to collect diffused light with a wide solid angle)
- Requires high concentrations of diffused light
- Backscattering not allowed

Bragg cell

Problem

- particles moving at the same velocity in two opposite directions will produce the same frequency shift !
- Motionless particules are not detected.

Bragg cell

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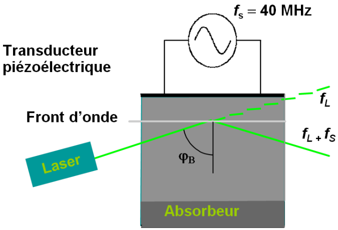
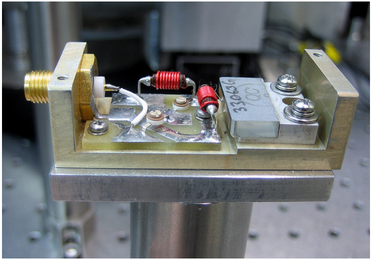
- particles moving at the same velocity in two opposite directions will produce the same frequency shift !
- Motionless particules are not detected.

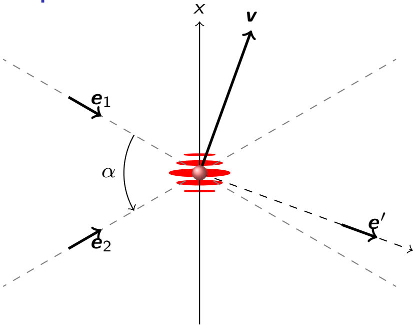
Solution

- Scrolling fringes thanks to the Bragg cell (acousto-optical modulator)
- Shift frequencies of the order of 40 MHz





Consequence on crossed beams



$$f_1 \simeq f\left(1 - \frac{\mathbf{v}}{c}\cdot(\mathbf{e}_1 - \mathbf{e}')\right)$$

$$f_2 \simeq f\left(1 - \frac{\mathbf{v}}{c}\cdot(\mathbf{e}_2 - \mathbf{e}')\right) + \Delta f$$

$$\Rightarrow \quad f_D = \Delta f + f\left(\frac{\mathbf{v}}{c}\cdot(\mathbf{e}_2 - \mathbf{e}_1)\right)$$

- When $V_x = 0$, $f_D = \Delta f \neq 0$
- Negative velocities $\rightarrow f_D < \Delta f$
- Positive velocities $\rightarrow f_D > \Delta f$

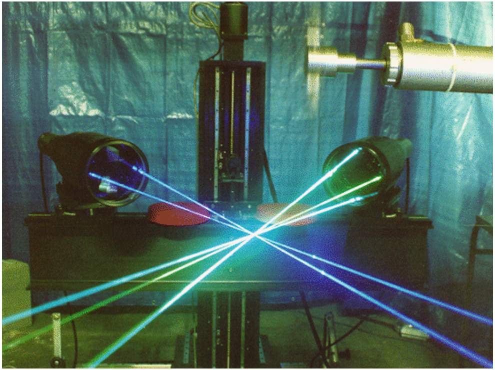
The interference fringes scroll with the velocity

$$U_f = d\Delta f$$

Two-component LDV

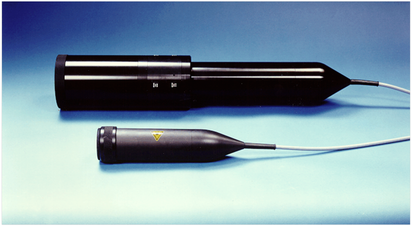
(laser Ar++, $\lambda = 488$ nm et 514,5 nm)

Three-component LDV



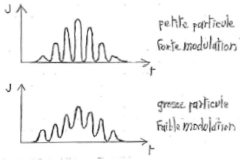
Compact probes

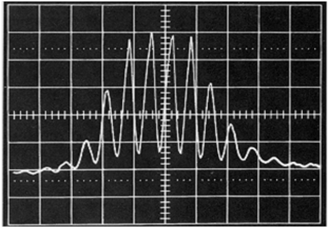
Fiber Flow probes (60 & 85 mm)



Small integrated 3D FiberFlow probe

Signal example





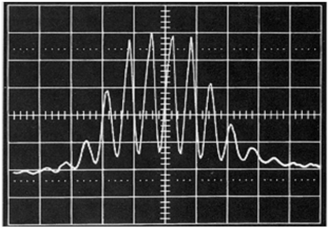
- ϕ sufficiently large to increase the scattered light intensity
- targeted if possible in the direction of a diffraction lobe
- $\phi \gg d \Rightarrow$ no optical contrast

Sources of noise

- Detection noise.
- Electronic and thermal noises of the pre-amplifying line.
- High order laser modes (optical noise).
- Diffused light out of the control volume, dirts, damaged window, ambient light, multiple particles, etc.
- Stray reflections (windows, lens, mirors, etc).

→ Laser power selection, seeding, optical parameters, etc, in order to optimise the signal over noise ratio.

Fourier analysis



$$I(t) = a\,(1 + \sin(2\pi f_D t)) \cdot G(t)$$

$$\downarrow$$

$$|\hat{I}(f)| = a\hat{G}(f) + a\,\delta(f - f_D) \star \hat{G}(f)$$

Electronic of detection

LDV main features

- Time-resolved point measurement
- The point measurement is a small ellipsoid (spatial coarsening)
- Non-uniform sampling frequency
- The flow must be seeded
- Linear law
- Expensive