Chapter 3

How to visualize your flow?

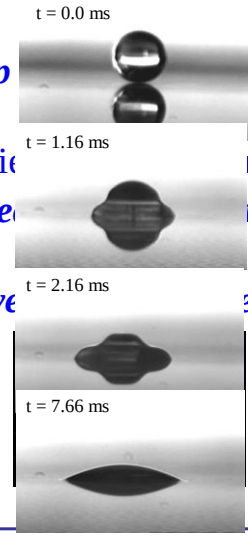
(*Flow Visualization Techniques*- the first step to approach the Physics of the Nature)

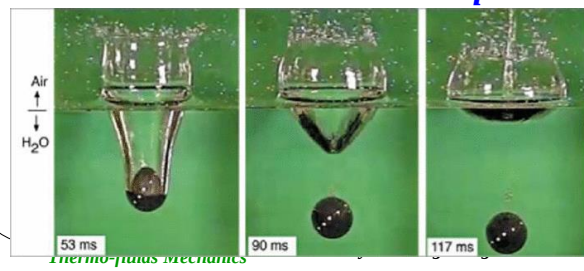
Contents

- Introduction
- Seeing is believing ?
- Flow visualization Methods
- Examples in the nature

Flow Visualization (I)

- "***Seeing is believing***"
- Flow Visualization is often the ***1st step*** investigation
- Flow Visualization can get a ***overall*** vie m.
- Flow Visualization may be used for ***ste dy*** or ***unsteady*** flow.
- Flow Visualization could be ***qualitative e.***

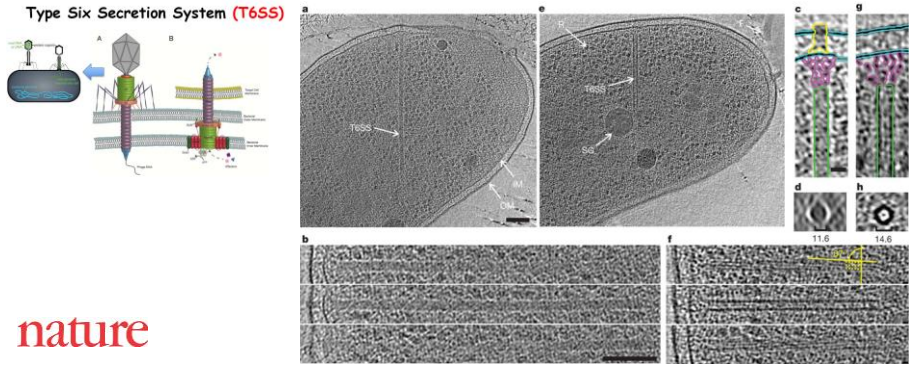




Flow Visualization (II)

https://www.youtube.com/watch?v=IA2BiCXqBHM

Electron cryotomographic (ECT) imaging of T6SS structures inside intact cells.

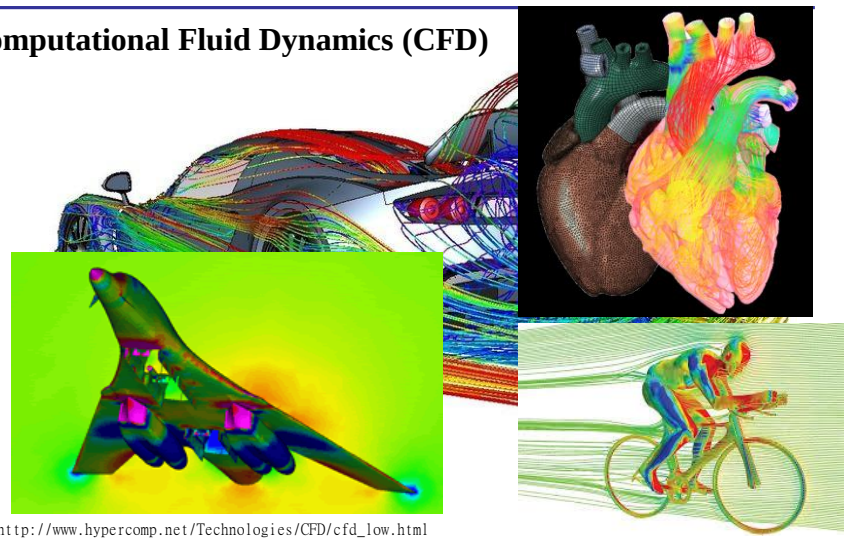


nature

M Basler *et al*. *Nature* **483**, 182-186 (2012) doi:10.1038/nature10846
Scale bars: **a**, 100 nm (applies to **a**, **e**); **b**, 100 nm (applies to **b**, **f**); **c**, 20 nm (applies to **c**, **d**, **g**, **h**).

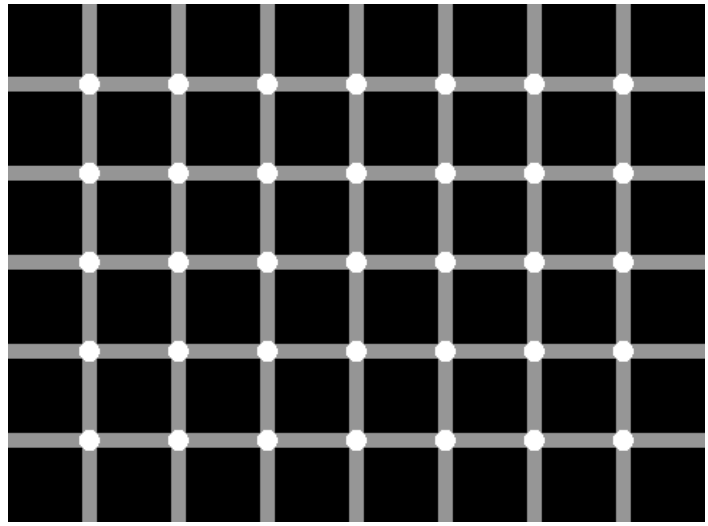
Flow Visualization (III)

Computational Fluid Dynamics (CFD)



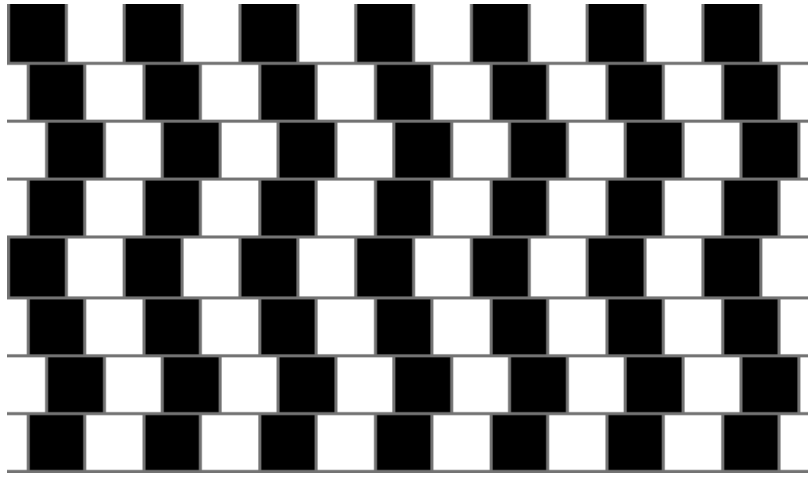
http://www.hypercomp.net/Technologies/CFD/cfd_low.html

Seeing is believing (I) ?

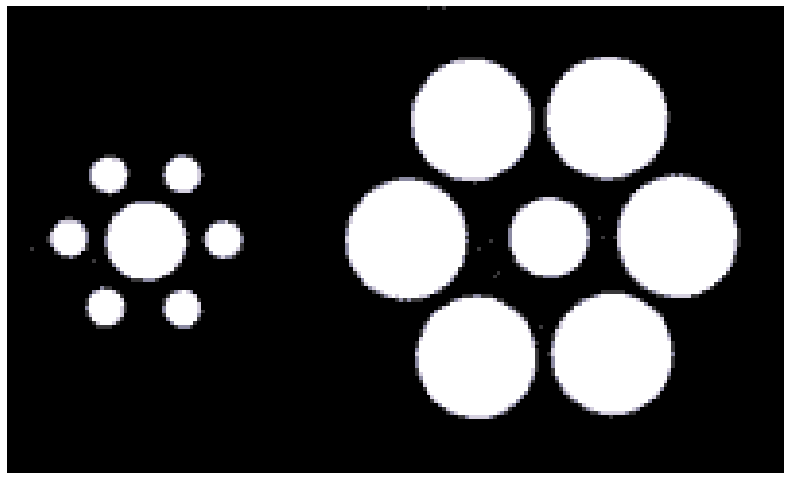


Seeing is believing (Ia) ?

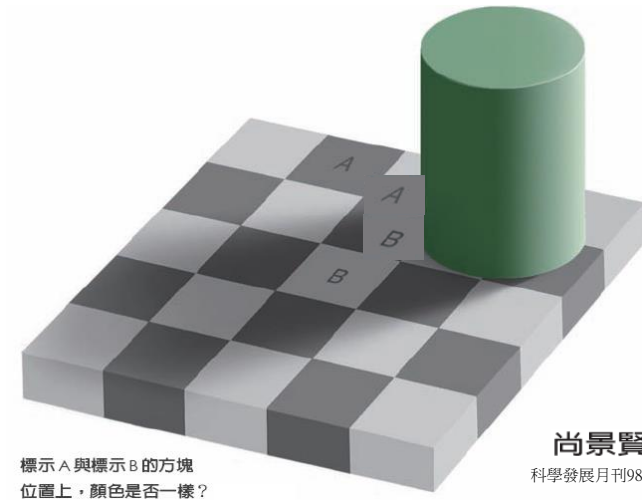
Seeing is believing (II) ?



Seeing is believing (III) ?



Seeing is believing (IIIa) ?



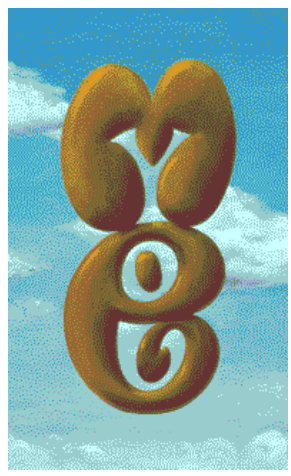
標示 A 與標示 B 的方塊
位置上，顏色是否一樣？

尚景賢
科學發展月刊98年4月號電子報

Seeing is believing (IV) ?

Seeing is believing (V) ?

Me & You and Teach & Learn

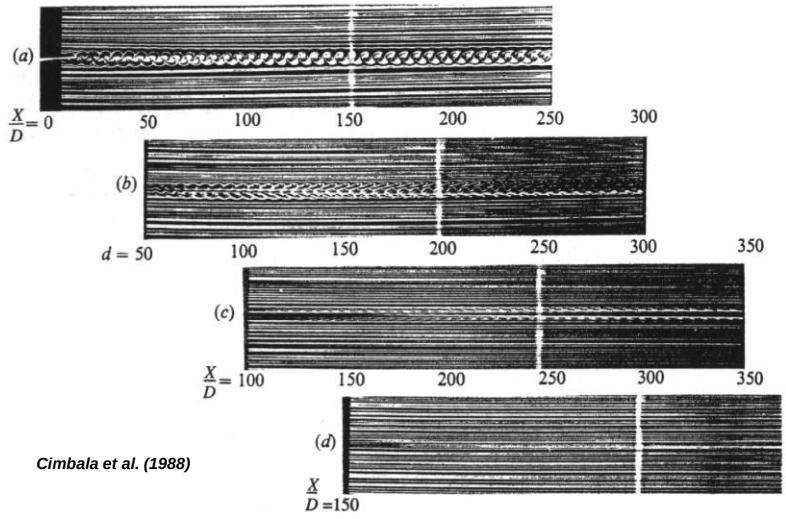


http://astrid-annabelle.blogspot.com/2008_06_01_archive.html

http://astrid-annabelle.blogspot.com/2008_06_01_archive.htmlNational Taiwan University Institute of Applied Mechanics

Modern Measuring Techniques of Thermo-fluids Mechanics *By An-Bang Wang*

Seeing is believing (VI) ?



Cimbala et al. (1988)

Flow Visualization (Ⅱ)

Elements of Flow Visualization:

- **Light source**：Sun-light , spot light, laser sheet
- **Objects**： seeded particles, Fluid molecules
- **Recording device**：drawings, Camera,Video Cam.,

H. M. the Queen

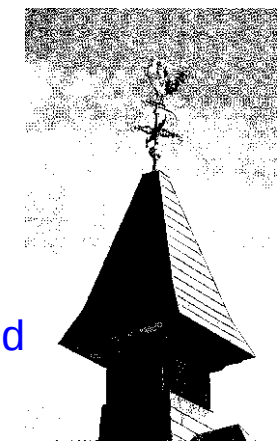
Flow Visualization (III)

Traditional Flow Visualization methods can be classified as :

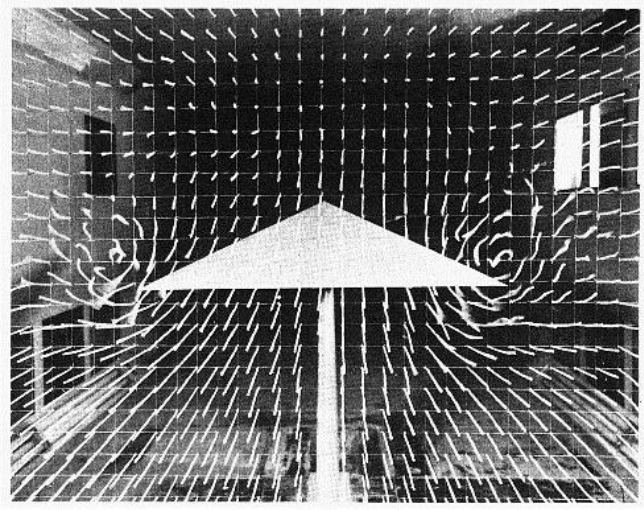
Stationary Probes	Tracer Methods
weather vane, tufts	weather ballon
Surface oil film, Liquid crystal paint	Particle tracers (e.g. hydrogen bubbles, smoke etc.), Dye injection
Optical methods (Shadowgraph, Schlieren, Interferometry)	Optical methods (Spark Tracer, LIF,…)

Examples of Flow Visualization Methods

1. Tuft method
2. Fluorescent method
3. Oil film method
4. Dye method
5. Smoke method
6. Hydrogen bubbles method
7. Shadow method
8. Spark Tracer method



Grid-and-Tuft



(From NASA)

Tuft method (I)

Character:

- One of the earliest & simplest technique of ***surface*** flow visualization.
- Point indicator of the ***local*** flow direction (especially for attached / separated flow).
- Effective in both gas and liquid flow.
- The spatial resolution determined by the number density of tuft array.
- The greater the observation distance the larger the tuft material must be.
- The tufts should be as ***light*** and ***flexible*** as possible to response to low flow velocity. But they should not too long to prevent tangles, and the color must ***contract*** well with background
- Problems of ***cling*** and ***gravity*** is the main considerations for the used (velocity) range.
- Stiffer tufts are needed in higher turbulent flow.

Tuft method (II)

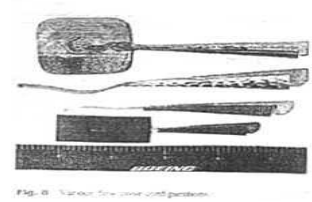
Parameters affect tuft behavior:

- Stiffness
- Motion rate
- Stability
- Response to turbulence
- Effects of centrifugal acceleration
- Static electric charges

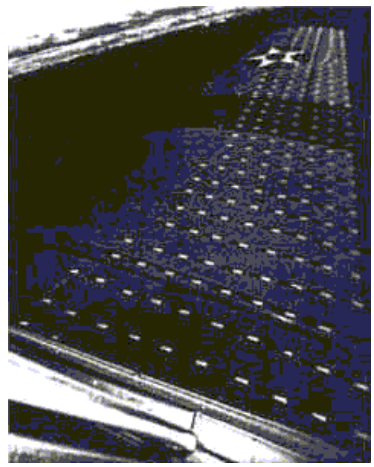
Tuft methods (III)

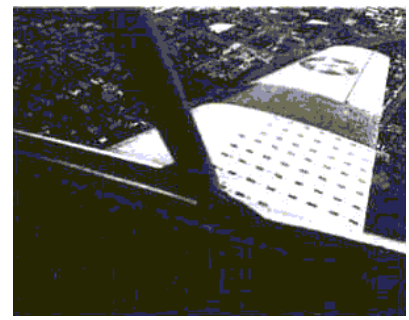
Types of Tufts methods:

- Conventional tufts
  Crochet yarn, heavy yarn, magnetic tape ....1" ~ 30' in length
- Fluorescent minitufts
  to minimize the intrusiveness and inertia-effect of tufts and magnify the photographic image. (by Crowder),
  resolution↗ for small-scale flow feature.
- Flow cones
  US patent , X-aero company,
  mass-production-based,
  flight-test studies

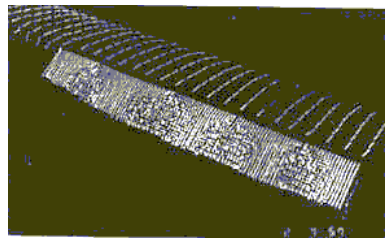


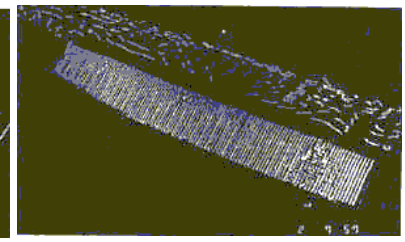
Flow cones visualization

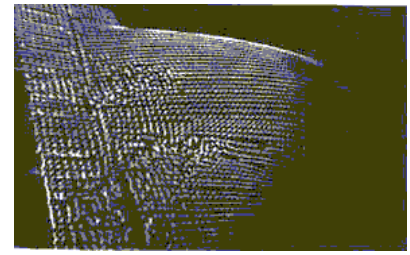




Fluorescent tufts visualization

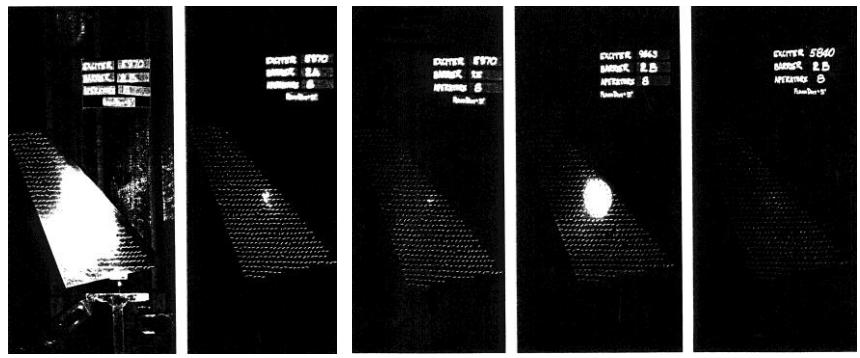






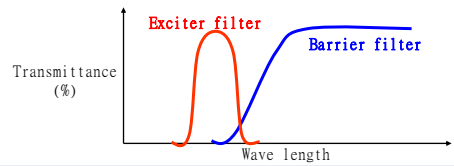
(From NASA)

Minituft Visibility



From Crowder (1989)

(a) 5970exciter, 2B barrier filters
(b) 5970exciter, 2A barrier filters
(c) 5970exciter, 2E barrier filters
(d) 9863exciter, 2B barrier filters
(e) 5840exciter, 2B barrier filters



Surface Tracing methods (I)

- Visualization is provided by means of a suitable coating on the surface of bodies in the flow, the fluid flowing around the body changes the coating, allowing determination of certain flow characteristics. These changes are either observed by the naked eye or photographic, cinematographic or videogenic recording techniques.
- Classification:
  (a) Chemical methods
  (b) Physical methods
  (c) Mechanical methods

Surface Tracing methods (II)

Chemical methods:

- Commonly used for liquid flow (especially for water)
- To change color of the visualization layer on the surface .This changes occur quickly or more intensely at sites of greater contact of two chemical substances, due either to higher concentration or to a more intense mixing process.
- Once the coasting has been used , it normally can ***not*** be reused.
- Examples :
  - Ferric chloride ($FeCl_3$)- inorganic gallic acid ($C_7H_6O_5$)
  - Potassium iodide (KI) - sodium thiosulfate ($Na_2S_2O_3$-$5H_2O$)
- Most of these substances are toxic !

Surface Tracing methods (III)

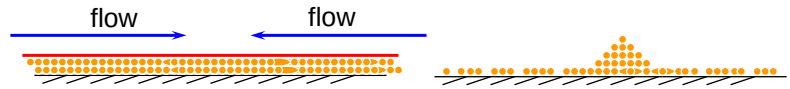
Physical methods:

- Used more frequently than chemical methods
- Based on ***sublimation, evaporation or dissolution*** of the surface coating on the body in the flow.
- Visualization for laminar/turbulent boundary layer (e.g., transition boundary).
- In practice of laboratory investigation , hexachloroethane (Cl_3CCCl_3, dull white color) is the most suitable coating .

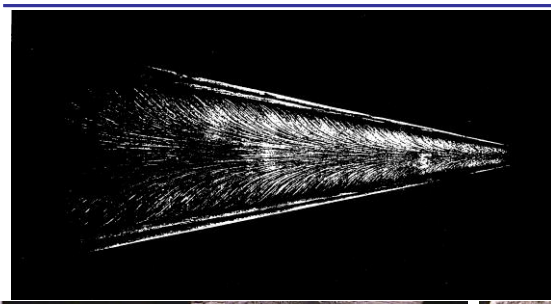
Surface Tracing methods (III)

Mechanical methods:

- Used both for gas and liquid flows.
- Oil-film and/or oil-dot method are the most commonly used method.
- This simple method works very well for determining transition regions as well as separation .
- Fine striae are produced in the paint determining the direction of local flow on the surface.

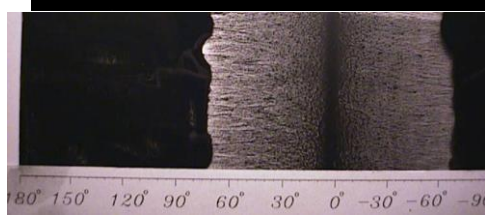


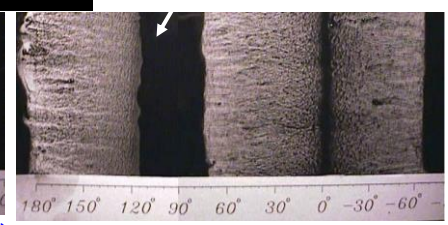
Oil-Film Method (I)



Delta wing
$\alpha = 15°$

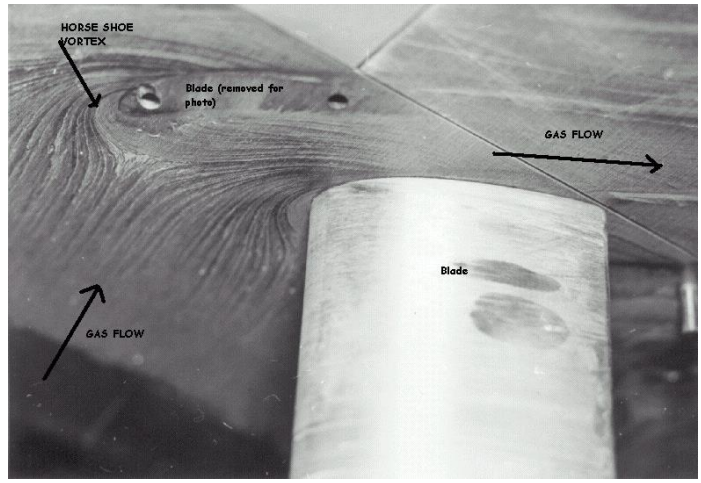
Cylinder Flow
w/ω control





Wang(1997)

Oil-Film Method (II)

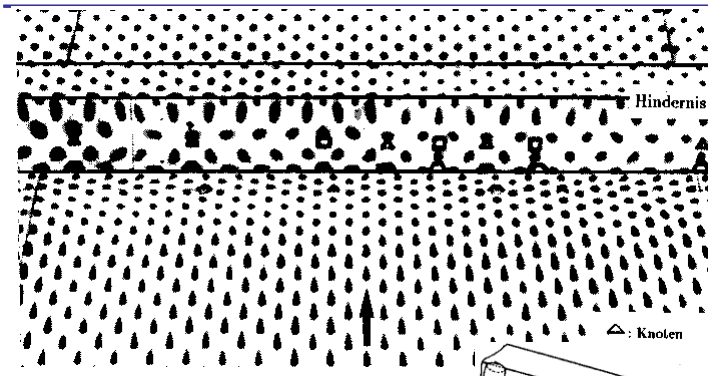


Ma=0.95, Re=600,000, by Dr. Rainer Kurz of Solar Turbines, U.S.A

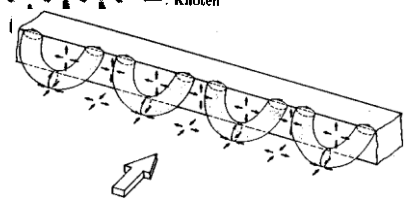
Oil-Film methods (III)

- For inclined or vertical surface, more attentions should be care
- The viscosity of the mixture (oil mined with pigment) is adjusted by trial and error for each application.
- Commonly used oil:
  - Kerosence,transmission oil, motor oil, paraffin, silicon oils, diesel fuel.....
- Commonly used ***pigments*** :
  - soots, titanium dioxide (TiO_2), lead chromate (depends on the color of working surface.)
- Addition of a small amount (~1 %) of the paint of oleic acid ($C_{17}H_{33}COOH$) reduces the tendency of particles to coagulate.

Oil-dot Method



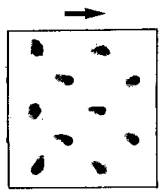
Flow over a square cylinder

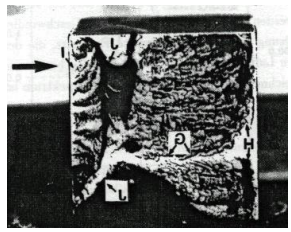


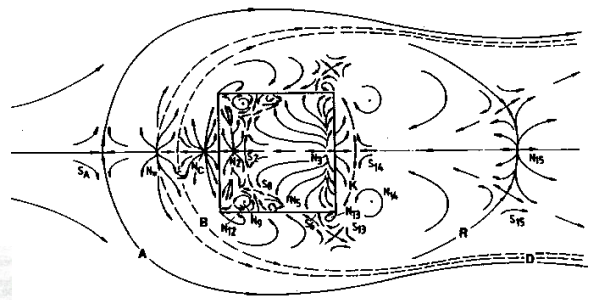
Martinuzzi (1992)

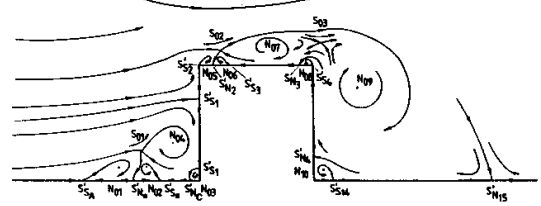
Oil-dot & oil-film Method

Flow over a cube









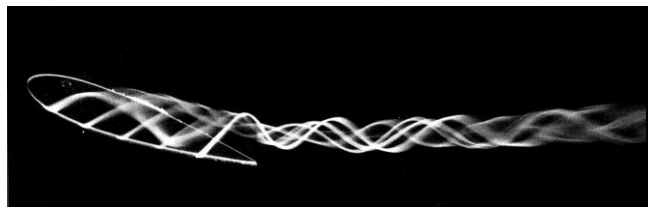
Martinuzzi (1992)

Dye Injection methods (I)

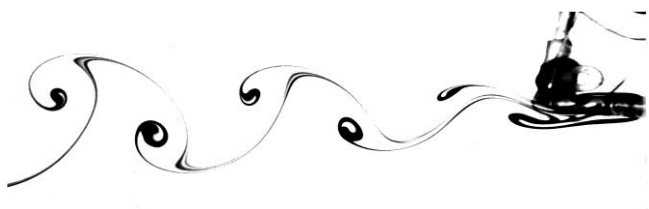
For liquid flow:

- Injection material :
  Ink, milk, Calcium, Permanganate, Aluminum power, Uranine-AP
- The injected tracer should have the same ***specific gravity*** as a low sink velocity.This could be slightly improved by controlling the temperature of the dye or working medium.
- Injection can be done using hypodermic needles or fine Pitot tubes.In shear layers ,the injection velocity must be matched to the flow velocity.

Dye-injection in liquids



(Werle 1974)



(Wang et al. 1996)

Dye Injection methods (II)

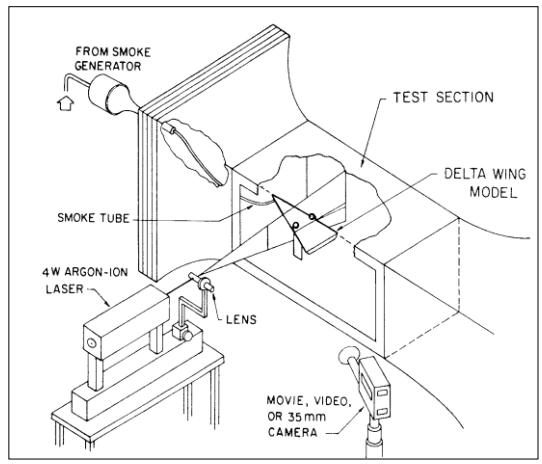
For gas flow:

- Injection material :
  smoke, oil smoke, aerosols, … etc.
- Guide line :
  - they should not be toxic!
  - high contrast necessary.
  - minimize disturbances produced by injection
  - suitable particle or droplet size
- As in accurate quantitative usage, e.g. LDA velocity measurement, the injected tracer must follow the flow to some degree of accuracy.

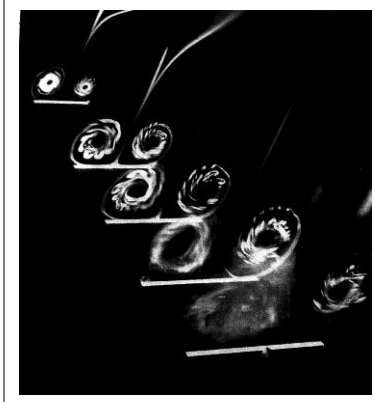
Dye-Injection in gas

Aircraft wake vortices can throw treacherous air turbulence into the paths of succeeding planes. In this NASA/FAA test, colored smoke makes the swirling airflow visible.
NASA LANGLEY RESEARCH CENTER
(from SCIAM 2002/02)

Smoke Method (I)



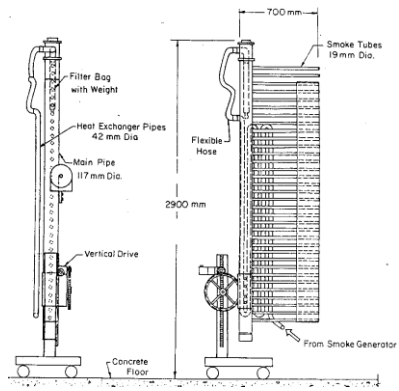
Laser-light sheet

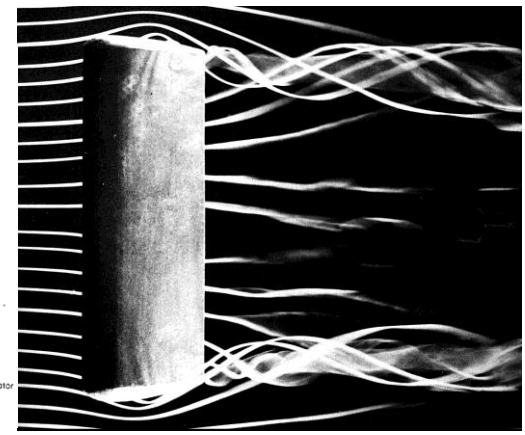


(by R. C. Nelson)

Smoke Method (II)

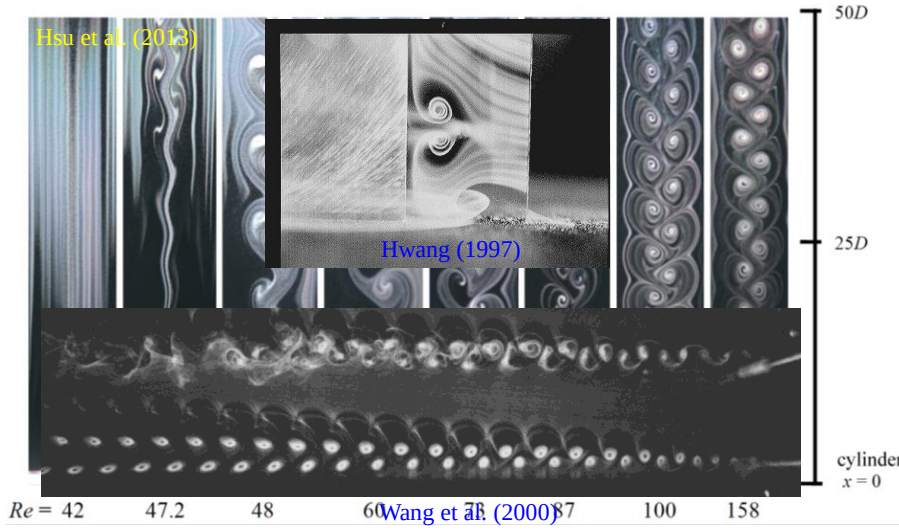
Smoke tube rakes





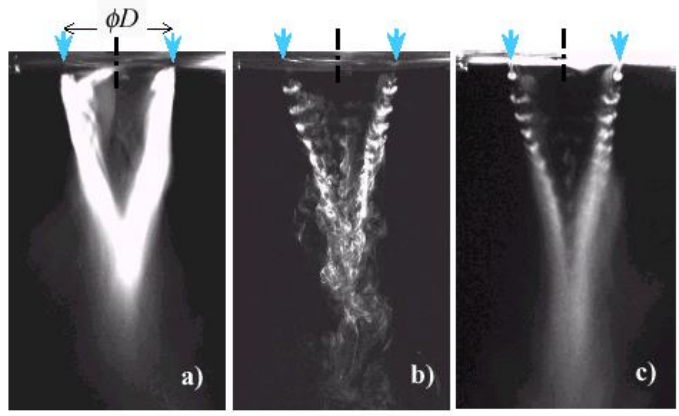
Head (1982)

Smoke-wire Method (I)

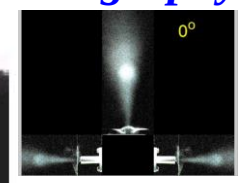


Smoke-wire Method (II)

Smoke wire method by different photography



Travnicek et al. (2002)

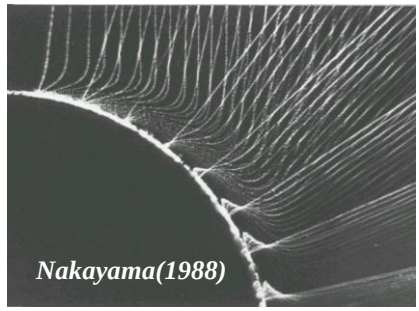


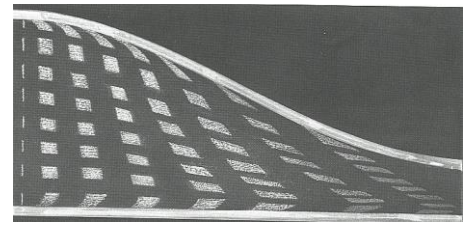
Annular synthetic jet (nozzle diameters: D = 40mm, and 38 mm). Acoustic excitation: f = 106 Hz, SPL = 66 dB. a) Mean flow pattern, 1 s-exposure, b) Instantaneous flow pattern (streaklines), c) Phase-multi-exposure of 106 flashes for the locked streaklines

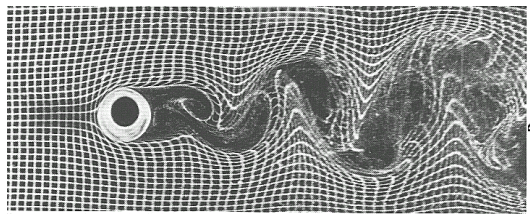
Smoke-wire Method (III)

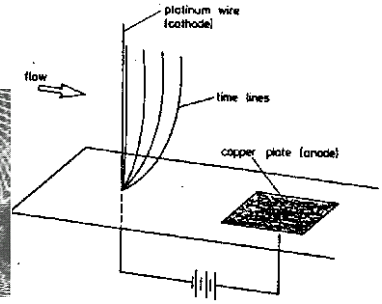
- ***Smoke wire: tungsten, platinum wire (50μm~200μm)***
- ***Configuration: twisted by thin wires to hold more oil (to maintain more time) or formed in a special construction***
- ***Oil: all kinds of non-toxic oil.***
- ***Constrains: the effective Reynolds number should be less than 20~30 to avoid the wake produced by the wire itself.***

Hydrogen bubbles methods (I)







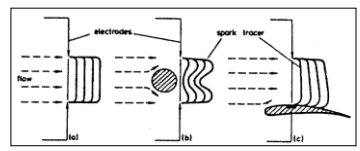


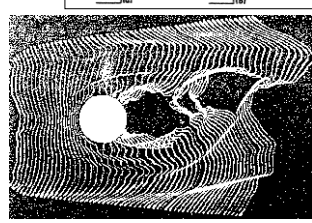
Hydrogen bubbles methods (II)

- In water flows, hydrogen bubbles can be used for flow visualization. A simple electrolysis instrument suffices.
- Anode: Platinum or tungsten (50μm~200μm)
  Electronics: - DC voltage adjustable (0~70V)
  - Pulsed operation is useful
  - Polarity reversal for removing oxidation.
- The bubble size depends on the voltage, the wire diameter, and the flow velocity.
  too small - not visible
  too large - buoyancy too large ($\propto d^3$), don't follow the flow ($\propto d^2$)
- fingernail polish can insulate sections of the anode .

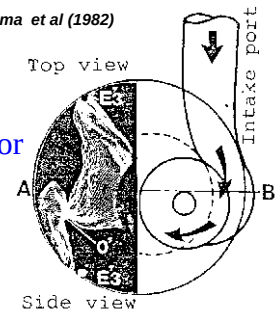
Spark Tracer Technique (I)

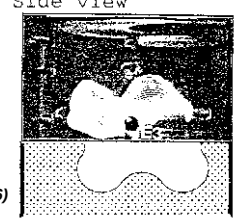
- Application:high speed air flow
- spark duration: ~100 μsec
- Measuring velocity: 1m/s ~ supersonic
- Tracer lighter than working fluid (main error source)





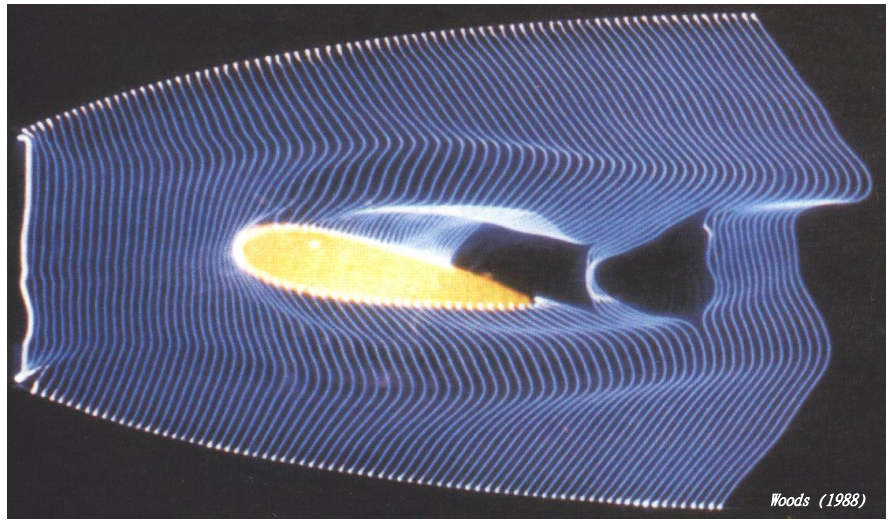
Najiyama et al (1982)



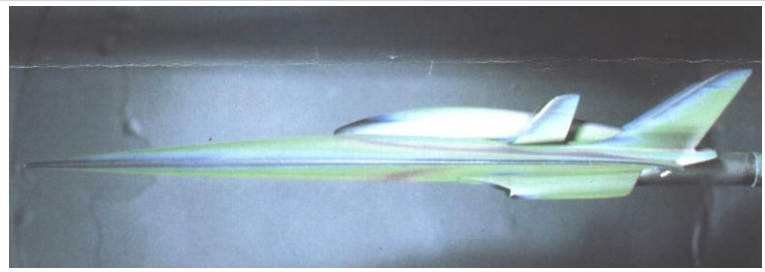


Nakayama et al (1976)

Spark Tracer Technique (II)



Thermal sensitive liquid crystal paint



(Sänger, Hypersonic space-shuttle test, source: DLR)

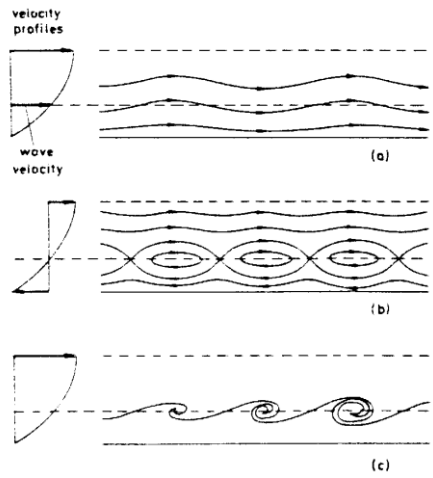
<30° black
30° red
32° yellow
35° green
40° blue
>47° black

Evaluation of flow patterns (I)

- Streamlines: line formed by drawing ***tangential to instantaneous velocity vector*** at all points in the flow.
- Streaklines (filament line) : connection of all fluid elements which have passed through ***a common point*** (achieved through dye injection)
- Path lines: Path traversed by ***a fluid element*** in the flow (obtained using long-time exposures)
- All three lines coincide if flow stationary.

Evaluation of flow patterns (II)

Reference system of observer is also important.



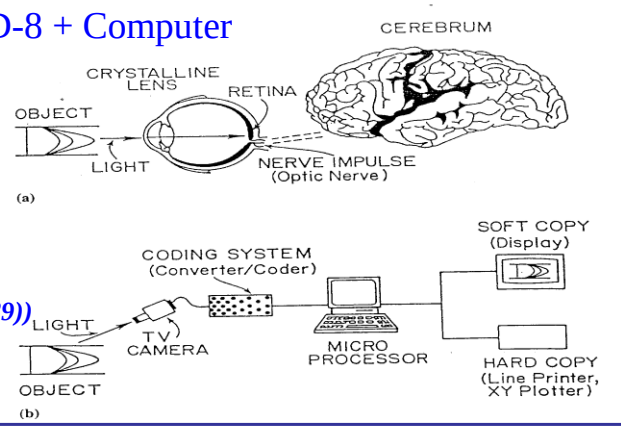
Streamlines for stationary observer

Streamlines for observer travelling at wave velocity

Streak lines

Recording Devices

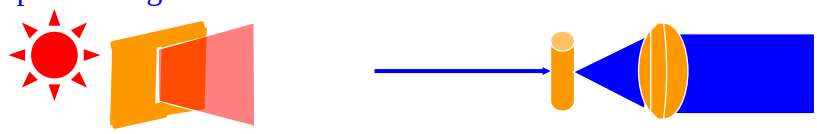
- Pencil & Paper
- Camera + Film + Lens
- CCD, V-8, D-8 + Computer



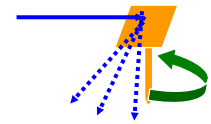
(*from Yang(1989)*)

Illumination

- Results from flow visualization are most commonly recorded by mean of photography or cinematography. Normal room lightening seldom provides sufficient illumination,and typical artificial light sources include spotlight, mercury arc lamps or laser.
- A plane of light allows a cross-section of the flow to be examined



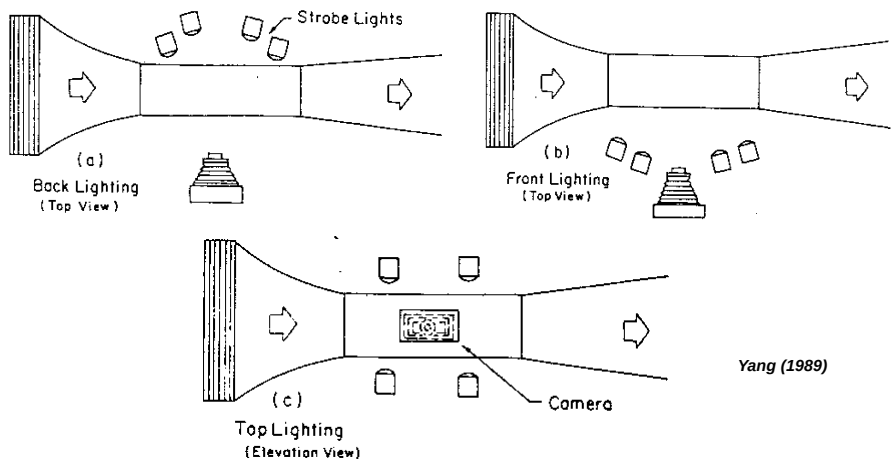
- Laser provide much higher light intensity.
- Mirrors can be used to capture several views of the flow in one exposure.



Light scattering phenomena

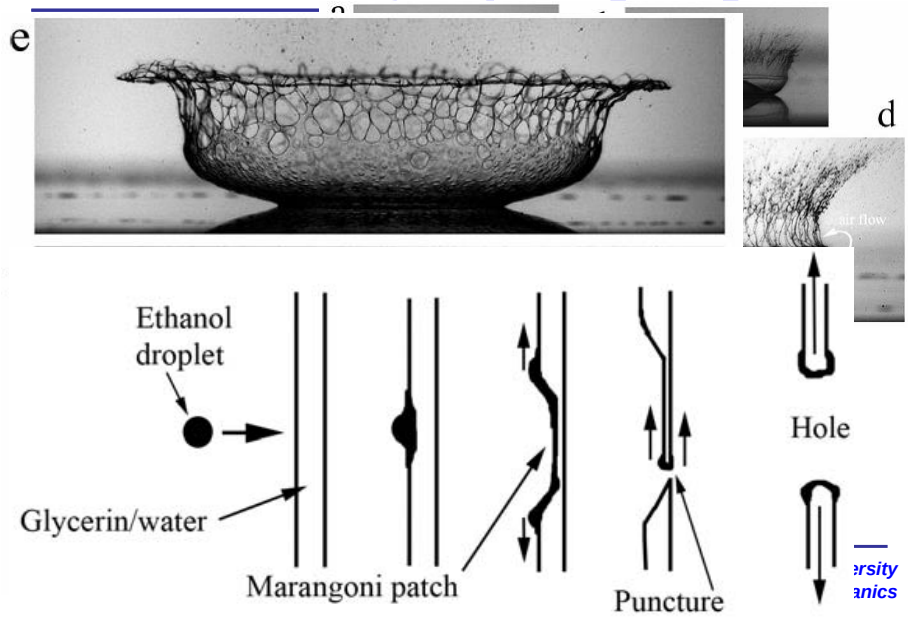
F e
la

Lighting & camera arrangement



Yang (1989)

Freezed Image of Drop Impact



Clear (Frozen) Image

- **Correct Focussing, Illumination and Exposure time (some μs ~ ms)**
- **Recording for moving body:**
- **High Speed Camera: high time resolution, low spatial resolution, high price, complex operation and maintenance**
- **CCD (charge-coupled device) Camera: low time resolution (standard：33ms/frame), high space resolution, low price, user-friendly.**
- **To avoid image blur**
  → adjustable shutter speed, using stroboscope or modified by image processing.

Optical Methods(I)

- Optical methods are especially advantageous because of their ***non-intrusiveness.***
- Principle of optical visualization methods is to make visible the light ray deviations (or wavefront deformations) due to the ***refractive index heterogeneities*** (caused by mixture of different fluids, pressure or temperature etc.) in a medium.
- Commonly used methods are ***Shadowgraphy, Schlieren*** and ***Interferometry.***

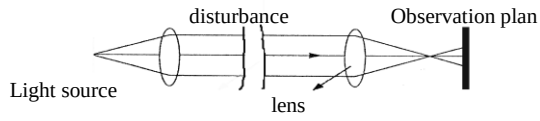
Optical Methods (II)

- Optical techniques are all integral method and give no information about local condition
- The investigated flow medium must be ***transparent.***

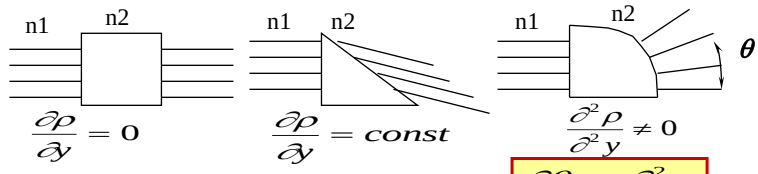
Method	Measuring Quantity	Remarks
Shadowgraphy	Second Derivative of Density	Simplest
Schlieren	Density Gradient	Suitable for large density gradient
Interferometry	Density difference	For small density gradient, complex, expensive

Shadowgraph Method

- **Configuration:**

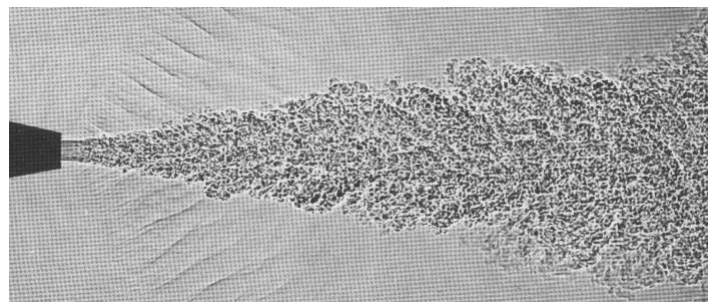


- **The Shadowgraph can be understood by considering the three following situations:**



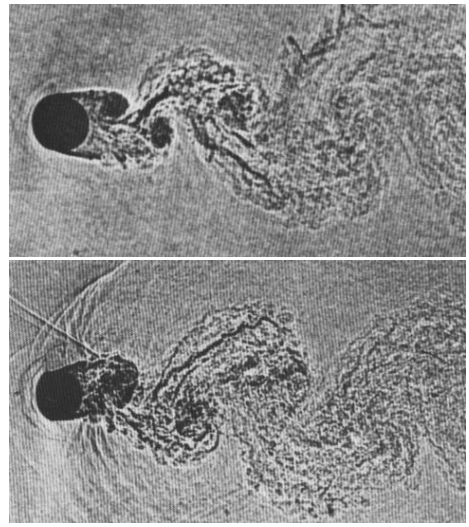
- **The Shadowgraph is based on the relation:** $\frac{\partial \theta}{\partial y} \approx \frac{\partial^2 \rho}{\partial^2 y}$
- **It yields sharper images with higher contrast than Schlieren method since all incident light is utilized in the image.**

Shadowgraph (I)



laminar helium jet into air (0.26 cm nozzle)
85kHz weak shock wave along 60°cone
from Chan & Lee (1972)

Shadowgraph (I)



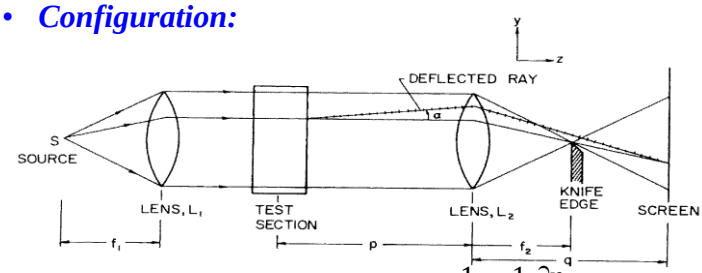
M = 0.45,
Re = 110,000

M = 0.64,
Re = 1,350,000

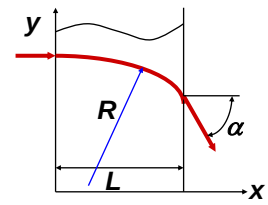
By Dyment et al.(1980)

Schlieren Method (I)

- ***Configuration:***



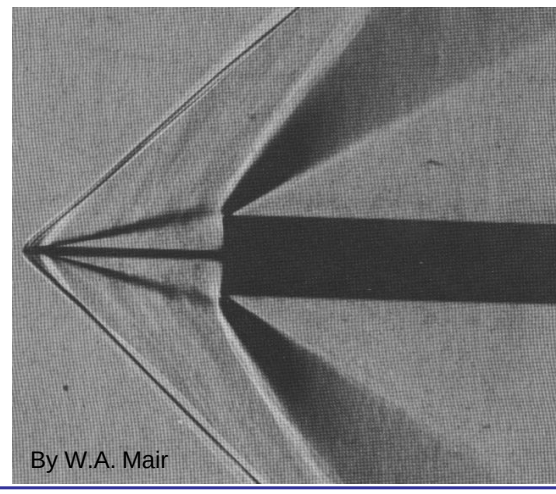
- ***Based on Fermat's principle:*** ($\frac{1}{R} = \frac{1}{n}\frac{\partial n}{\partial y}$)
  The change of light intensity on the screen
  $\Delta I/I = \alpha = (L/n)(dn/dy) \propto (L/n)(d\rho/dy)$
- ***negative density gradient : dark***
- ***positive density gradient : light***



Schlieren Method (II)

- change the orientation of knife edge will change the light/dark image on the observer plane, also charge the measure of space derivative of ρ
- The Schlieren method is used primarily for qualitative measurement.
- The color Schlieren systems are more sensitive for visual viewing since the eye can discriminate a larger number of colors than shades of one color. For the color Schlieren system, the light source must be a slit rather than a point source.
- Large, good quality lenses are very expensive and therefore it is commonly using mirrors instead of lenses. Long focal length spherical mirrors are suitable for this purposes.

Schlieren photo

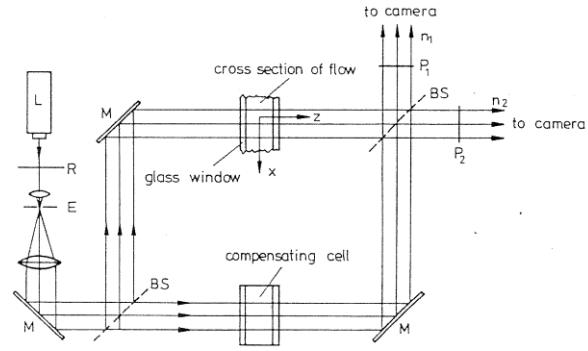


M = 1.96

Interferometry Method

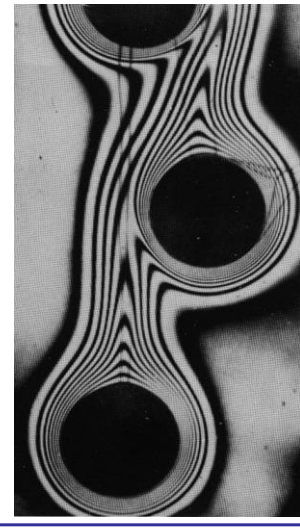
- **Configuration:**

Mach-Zehnder Interferometer



- **If density variation are present, then phase differences between the object path and reference path result, which lead to interference patterns after recombination.**

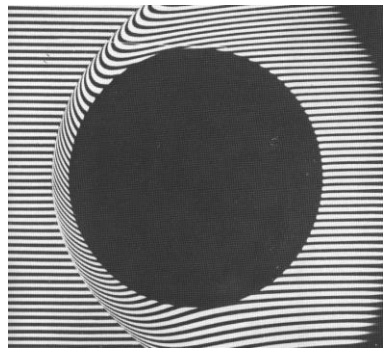
Interferogram



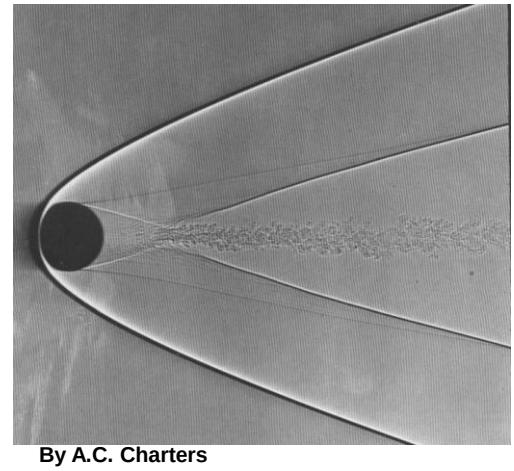
Eckert & Soehngen (1948)

Interferogram & Shadowgraph

1/2” sphere M = 5.7

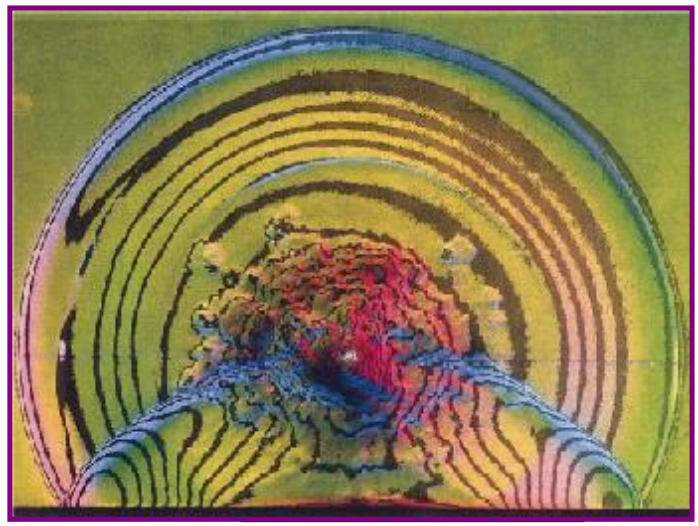


M = 4.01



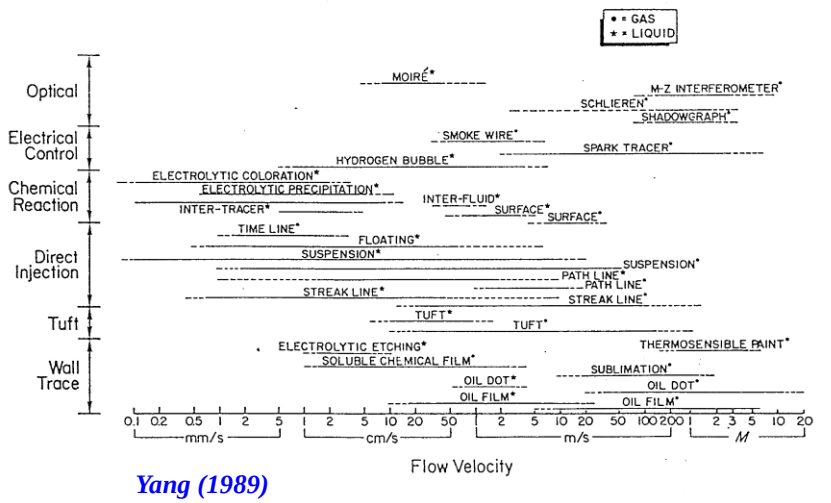
By A.C. Charters

Interferometry & Schlieren



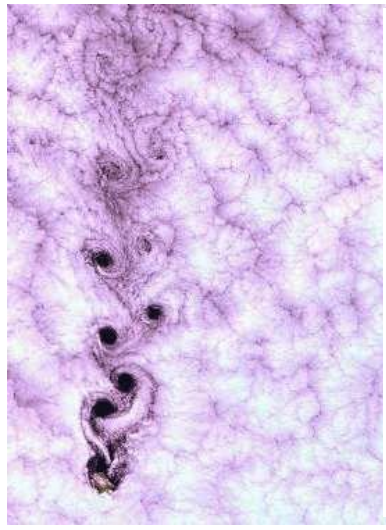
Blast waves
By Klein & Takayama
(2001)

Applicable range for various Flow Visualization Methods



Yang (1989)

Von Karman Vortex Street in nature



A rare meteorological phenomenon caught by LANDSAT 7 on 9/15/1999. In the southwest of the scene is Alejandro Selkirk Island, a squarish island that rises almost vertically 1 mile above the southern pacific. A boundary layer that sandwiches a saturated, unstable layer of clouds between two more stable layers is broken by the island, causing a formation of vortices known as a Karman Vortex Street.

Kelvin-Helmholtz roll-ups in a cloud formation

Kelvin-Helmholtz roll-ups as seen in a cloud formation.
The picture is from the National Center for Atmospheric Research.

Formation of trailing vortices in the wake of a C-130 Hercules

1993 Aviation Week & Space Technology by James E. Hobbs, from Lockheed Aircraft service Co., Ontario, California.
The plane is ejecting flares during a test of an infrared missile warning and self-protection system installed on a C-130 Hercules.
The trailing vortices formed in the wake are clearly visible.

Wake by MIG-29 fighters

2005, 7月30日，俄羅斯莫尼諾航空展，一個俄羅斯米格29戰鬥機編隊在空中做列隊表演。莫尼諾距莫斯科大約40公里。這次航展是為了紀念第二次世界大戰勝利60週年

Scock wave by F-4 fighter

F-4 Phantom II Caught Breaking the Sound Barrier.

Using a 35mm camera, a telephoto lens and ASA 400 film, Pat Maloney, an engineering planner, photographed an F-4 Phantom II at the moment it broke the sound barrier at the Annual Point Magu Naval Air Station Air Show. "The photograph of the visible shock wave is rare." stated Maloney. "It required a humid day, split second timing and no small measure of luck." Maloney frequently practices photography at the many air shows he attends.

TMAA SCAN

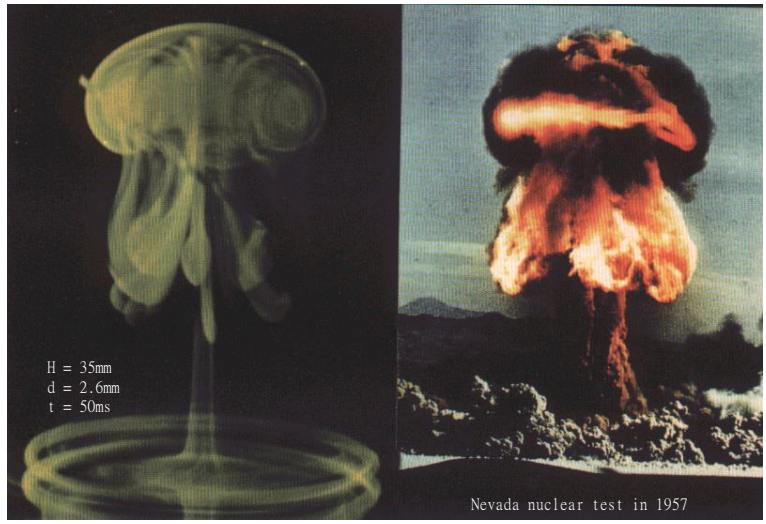
Surface wave

This spectacular picture of a B1 bomber flying over a lake (sea?) appears to show the wake generated by the wave field emanating from the airframe. What is wrong with this picture?
(by Jan-Olov Newborg , from Stockholm).

Sport

6月26日，美國加利福尼亞州聖塔克拉拉的游泳大獎賽上，世界記錄保持者Aaron Peirsol正在進行仰泳的比賽

Vortex ring formation



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- **Merzkirch, W.,** Flow Visualization, Academic Press, New York, 1974.
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- 王安邦等十六人合輯, 雷射熱流量測基礎訓練課程講義, NSC, NTU-IAM, Taipei, June 30 – July 11, 1997
- **Conference Proceedings and Journal Papers**
  - (Proceedings of the International Symposium on Flow visualization, Proceedings of the Pacific Symposium on Flow Visualization and Image Processing…..)